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The Journal of
THE ROYAL AERONAUTICAL SOCIETY

CONTENTS OCTOBER 1950

AIR SURVEY
PROFESSOR C. A. HART, T.D., D.Sc.(Eng.), Ph.D., M.I.C.E., F.R.I.C.S.

REDUX BONDING OF AIRCRAFT STRUCTURES
C. J. MOSS, B.Sc.

NOTE ON THE TIME REQUIRED TO MAKE LEVEL SPEED MEASUREMENTS WITH A TURBINE JET AIRCRAFT
K. J. LUSH, B.Sc., D.I.C.

REVIEWS CORRESPONDENCE

LONDON
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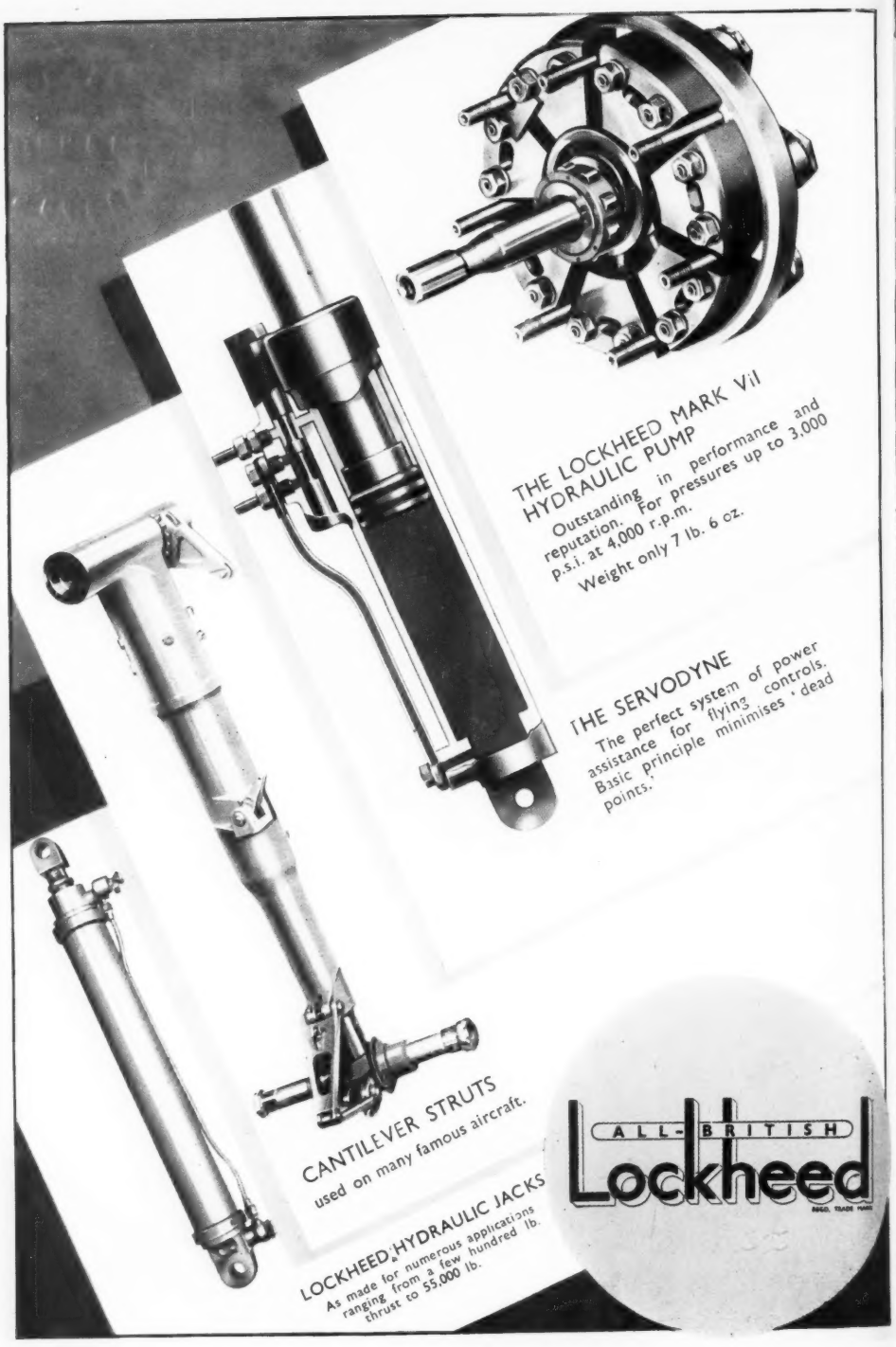
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THE ROYAL AERONAUTICAL SOCIETY

GRADUATES' AND STUDENTS' SECTION

October 1950

SOME NOTES ON THE TERMS "*g*" AND "INERTIA"

By M. C. CAMPION, B.Sc.(Eng.), Grad.R.Ae.S.

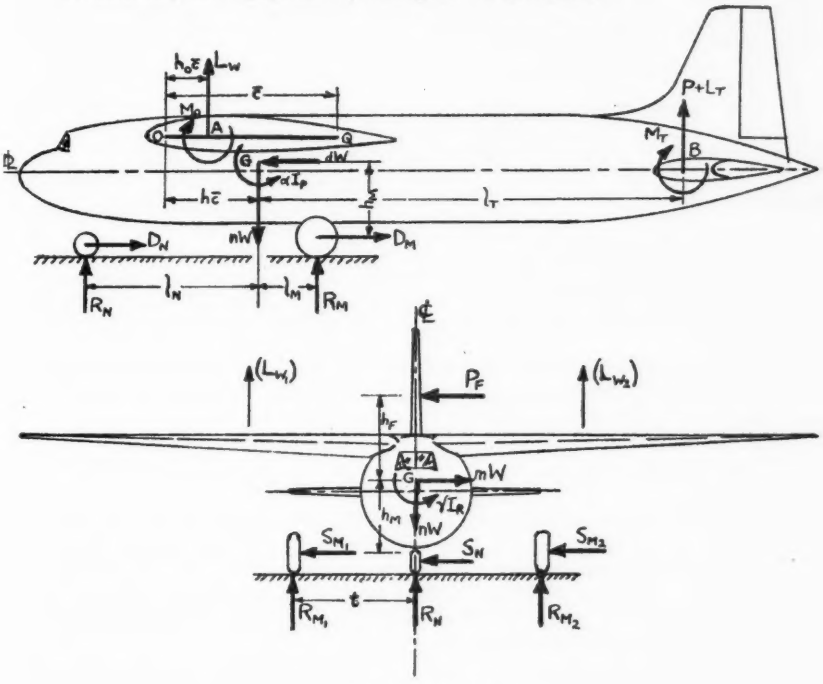
PART III

(Parts I and II were published with the August issue of the Journal)

III—*The loads on an aeroplane, and the resulting inertia factors*

(*i*) This part of the paper describes the use of inertia loads and moments to balance the system of applied loads and moments on an accelerating aircraft. The method of estimation of the total inertia factors on any part of a rigid aircraft is also indicated.

The units used throughout are those derived in Part I, namely pounds weight (for force), pounds (for mass), feet (for distance), "*g*'s" (for linear acceleration) and "*g*'s/foot" (for angular acceleration).



Figs (*i*) and (*ii*)

(*ii*) The forces acting on an aircraft are due to aerodynamic loads, thrust and ground reactions, and are mostly shown in Figs. (*i*) and (*ii*). Since the derivation of the air loads is purely an aerodynamic problem, it will not be discussed here in detail[1].

[1] It is hoped that a later paper will be published in these pages, giving an account of the aerodynamic problems of estimating these loads.

The resultant air load, L_W, on the wings and fuselage, will act at some centre of pressure, but it is more convenient to consider the load applied at the aerodynamic centre, A, of the aircraft (less tail), together with its moment, M_0, about A.

The positions of A and G (the centre of gravity of the aircraft) are defined in terms of the distances, $h_0\bar{c}$ and $h\bar{c}$, from the leading edge, O, of the *standard mean chord*, OQ.

Similarly, the tail load, L_T, required to trim the aircraft is applied, not at the centre of pressure, but at B, the aerodynamic centre of the tailplane, together with its moment, M_T, about B. An impulsive or manœuvring load, P, on the tailplane, then acts at B (and has no moment about B).

The fin load, P_F, and its moment, M_F (not shown in the diagram) are treated in the same manner.

The other air loads and moments, not shown, are:

M_R the rolling moment, about the axis of symmetry, of aileron loads or unequal loading on the halves of the tailplane,

M_Y the yawing moment, about the centre of gravity, G, of the pressure distribution on the fuselage, wings and nacelles,

P_S the side load due to this distribution,

D the drag of the aircraft.

The ground reactions which can be applied to the aircraft are:

R_M, D_M, S_M the total vertical, drag and side loads on the main undercarriage units (suffixes 1 and 2 denote the loads on the separate port and starboard units),

R_N, D_N, S_N the total vertical, drag and side loads on the nose wheel unit (or corresponding loads on the tail wheel, if the aircraft is so equipped).

The vertical loads act at the points of contact, but the points of action of the drag and side loads are arbitrarily chosen in relation to the design loads, and are specified in the appropriate handbook of strength requirements[2].

(*iii*) In steady level flight, the total lift on the aircraft must equal the weight, W, and the total moment about the centre of gravity, G, must be zero. In the notation of Fig. (*i*):

$$L_W + L_T = W \quad . \quad . \quad . \quad (9)$$

$$M_0 + L_W \ (h - h_0)\bar{c} + M_T - L_T . l_T = 0 \quad . \quad . \quad . \quad (10)$$

The force acting on any component (mass m pounds) of the aircraft is its weight, m pounds weight. But from equation (7), the inertia force on a component of m pounds mass is nm pounds weight, where n is the acceleration in "g's." Hence the effect of weight in steady level flight is identical to the inertia effect when the acceleration is one "g." Steady level flight is therefore frequently described as "flight at one g."

(To be continued)

Note.—The author is indebted to F. Grinsted (*Assoc. Fellow*) and others, for drawing attention to the following error in Part I (August 1950 JOURNAL):—
In equations (4) and (5) of Part I, the coefficient 32.2 should be 1/32.2.

[2] Air Publication 970, for military aircraft, and the Civil Airworthiness Requirements of the Air Registration Board, for civil aircraft, are the relevant British handbooks.

THE ROYAL AERONAUTICAL SOCIETY
4 HAMILTON PLACE, PICCADILLY, LONDON, W.1. GROSVENOR 3515-9

NOTICES OCTOBER 1950

CONTENTS OF THE OCTOBER JOURNAL

Air Survey, Professor C. A. Hart, T.D., D.Sc.(Eng.), Ph.D., M.I.C.E., F.R.I.C.S.

Redux Bonding of Aircraft Structures, C. J. Moss, B.Sc.

Note on the Time Required to make Level Speed Measurements with a Turbine Jet Aircraft, K. J. Lush, B.Sc., D.I.C.

Reviews.

Correspondence.

The Council are particularly anxious to encourage members of the Society to support their own Journal by contributions to it of articles and papers on any aspect of Aeronautics. For that purpose they have set aside £250 a year in the form of premium awards to the authors (members or non-members) of such papers as some reimbursement for the work which has been done by the author. These premium awards are not fixed but vary from five to twenty guineas normally. It is hoped therefore that those members who have written papers on their special subjects will consider their own Journal in the first place.

THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY

It is regretted that with the increasing costs of production it has been found necessary to increase the price of the JOURNAL OF THE SOCIETY.

From January 1951 (Volume LV, Number 481) the price will be increased from 7s. 6d. to 10s. 0d. for each number.

The new rates from January 1951 therefore will be:—

Single Copies: 10s. 3d. each including postage (home or abroad)

Annual Subscription: £6 3s. 0d. including postage (home or abroad)

THE AERONAUTICAL QUARTERLY—Parts I and II, Volume II

Part II, Volume II of "The Aeronautical Quarterly" is still available from the offices of the Society at 7s. 9d. a copy to members of the Society, post paid, or 10s. 3d. to non-members, post paid.

The Contents of Part II are:—

Critical Mach Numbers for Swept-Back Wings	S. Neumark
General Performance Reduction Equations for Reciprocating-Engined Aircraft with Constant-Speed Propellers ...	W. J. Annand
The Axially-Symmetrical Supersonic Flow Near the Centre of an Expansion	N. H. Johannesen and R. E. Meyer
Note on the Dependence of Flap Hinge Moment Derivatives on Hinge Position	W. J. Duncan
On the Chordwise Lift Distribution at the Centre of Swept Wings	D. Küchemann and J. Weber
Amendments to: "A Note on the Bending Moment Induced in the Booms of a Spar at the point of Application of a Concentrated Load" (Volume I Part IV) ...	H. F. Winny

The Contents of Part I Volume II, copies of which are still available, are:—

Two-Dimensional Theory of Stiffened Plates	Chang O'Chou
The Whirling of a Spinning Top	J. Morris
The Possibility of the Determination of Rate of Climb from Acceleration Measurements in Level Flight ...	E. C. Pike
A Note on Subsonic Aerofoil Theory	John W. Miles
Theory of an Oscillating Supersonic Aerofoil	Geoffrey L. Sewell
The Linearised Theory of Conical Fields in Supersonic Flow, with Applications to Plane Aerofoils	S. Goldstein and G. N. Ward

A few copies of Parts I to IV, Volume I are still available and members are reminded that a strictly limited edition only of "The Aeronautical Quarterly" is printed and numbers cannot be reprinted in any circumstances. An annual subscription therefore is advisable.

ANGLO-AMERICAN AERONAUTICAL CONFERENCE—1951

The Third Anglo-American Aeronautical Conference, convened jointly by the Royal Aeronautical Society and the Institute of the Aeronautical Sciences (of America), will be held at Brighton, Sussex, during September 1951.

Previous Conferences have been held in London in 1947 and in New York in 1949.

Further information will be issued as soon as it is available.

MEMBERS' NEW APPOINTMENTS

W. J. C. Speller, *Associate Fellow*—Instructor, College of Aeronautical Engineering.

Group Captain G. E. Watt, *Fellow*—Command Engineer Officer, Fighter Command, Royal Air Force.

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY—LECTURER REQUIRED

Applications are invited by Imperial College of Science and Technology (University of London), Department of Aeronautics, for a post as Lecturer. The salary is within the range £600/£50/£1,150, with F.S.S.U. and family allowance, with a starting salary according to qualifications. The emphasis in the candidate's interests and experience should be on the theory of aeronautical structures, and the candidate will be required to carry out research and teaching to advanced students in aspects of applied mechanics applicable to aeronautical structures. As the appointment is intended, *inter alia*, to give opportunity to conduct research, originality of mind and a wish to undertake such work, are essential qualifications. Applications should be addressed to the Head of Aeronautics Dept., City & Guilds College, Exhibition Road, South Kensington, S.W.7.

LECTURES—AUTUMN 1950

MAIN LECTURES

(At 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, London, S.W.1, unless otherwise stated. Tea will be served at 5.30 p.m.)

Thursday, 19th October 1950—Use of Wind Tunnel Model Data in Aerodynamic Design, R. Hills, B.A., A.F.R.Ae.S.

Tuesday, 7th November 1950—AT BELFAST—Aircraft Metallic Materials under Low Temperature Conditions, Major P. L. Teed, F.R.Ae.S.
At the College of Technology, Belfast, at 6.30 p.m.

Thursday, 23rd November 1950—Rockets and Assisted Take-off, A. V. Cleaver, A.R.Ae.S.

Thursday, 7th December 1950—A DISCUSSION—The Relative Merits of Centrifugal and Axial Compressors for Aircraft Gas Turbines, H. Pearson, B.A., A.F.R.Ae.S. and Dr. E. S. Moult, B.Sc., F.R.Ae.S., M.I.Mech.E.

Thursday, 14th December 1950—Clear Air Turbulance Over Europe, Dr. G. S. Hislop, B.Sc., A.R.T.C., M.I.Mech.E., A.F.R.Ae.S.

SECTION LECTURES

(At 7 p.m. in the Library of the Royal Aeronautical Society, 4 Hamilton Place, London, W.1, unless otherwise stated.)

Tuesday, 10th October 1950—Problems of High-Speed Flight, G. T. R. Hill, M.C., M.Sc., F.R.Ae.S., M.I.Mech.E.

Tuesday, 24th October 1950—Aircraft Riveting, H. Giddings, A.F.R.Ae.S.

Tuesday, 14th November 1950—Operational Problems of Public Transport Helicopters, R. H. Whitby, B.Sc., A.R.C.S., D.I.C., A.F.R.Ae.S.

Tuesday, 28th November 1950—Metal Adhesive Processes, F. H. Parker.

Tuesday, 5th December 1950—Aircraft Production, Prof. J. V. Connolly, B.E., F.R.Ae.S.

GRADUATES' AND STUDENTS' LECTURES

(At 7.30 p.m. in the Library of the Royal Aeronautical Society, 4 Hamilton Place, W.1, unless otherwise stated. Visitors are welcome to attend.)

Thursday, 26th October 1950—The Aerodynamics of Compressor and Turbine Cascades, J. A. Dunsby, B.Sc., D.I.C., Grad.R.Ae.S.

Thursday, 9th November 1950—Work in the High-Speed Tunnel, F. G. Irving, B.Eng., Grad.R.Ae.S.

Thursday, 30th November 1950—High-Speed Flying, Sqdn. Ldr. J. Derry, D.F.C.

Tuesday, 12th December 1950—Film Show, by W. Courtenay, O.B.E., M.M., A.R.Ae.S.

BRANCH LECTURES AND NOTICES

Notices of Branch Lectures and Meetings for inclusion in the Monthly Notices of the Society must be received by the 20th of the preceding month. The Honorary Secretaries of all Branches are asked to inform the Society of their arrangements for meetings so that a complete list of Branch meetings may be given.

BIRMINGHAM BRANCH

Monday, 25th September 1950—*Visit to* Boulton Paul Aircraft Ltd., Wolverhampton—at 7.30 p.m.

Friday, 27th October 1950—A DISCUSSION on Aeronautical Experiences—led by Messrs. Baldwin, Garrat-Reed, Yoxall and Bostock.

At the Chamber of Commerce, Birmingham, at 7.30 p.m.

Friday, 24th November 1950—A Review of Aerodynamic Cleanness, E. J. Richards, M.A., B.Sc., F.R.Ae.S.
At Wolverhampton, at 7.30 p.m.

Friday, 15th December 1950—Radar and Kindred Pilot Aids.
At the Chamber of Commerce, Birmingham, at 7.30 p.m.

BRISTOL BRANCH

Monday, 23rd October 1950—Forty Years of British Aviation, Sir Frederick Handley Page, C.B.E., Hon.F.R.Ae.S., F.C.G.I.

Tuesday, 31st October 1950—Some Problems in Helicopter Aerodynamics, W. Stewart, B.Sc.

Wednesday, 15th November 1950—Present Trends of Industrial Gas Turbine Development, R. G. Voysey, A.C.G.I., D.I.C., Wh.Sc., A.M.I.Mech.E. (*Joint Meeting with the Institutions of Mechanical and Electrical Engineers to be held at the Royal Fort Physics Laboratory, Bristol, at 7 p.m.*)

Monday, 27th November 1950—(Section Lecture)—Landing Gear Design, H. G. Conway, M.A., F.R.Ae.S., A.M.I.Mech.E.

Monday, 4th December 1950—Physical Aspects of Compressible Flow and Shock Waves, Joseph Black, M.Sc., A.F.R.Ae.S.

In the Conference Room, Filton House, The Bristol Aeroplane Co. Ltd. at 6 p.m. unless otherwise stated.

BROUGH BRANCH

Wednesday, 15th November 1950—Aircraft in Future Warfare, Air Marshal Sir Robert Saundby, K.B.E., C.B., M.C., D.F.C., A.F.C.

Wednesday, 6th December 1950—Members' " Lecturette " Night.
In the Lecture Hall, Electricity Showrooms, Ferensway, Hull, at 7.30 p.m.
Admission is by ticket only.

COVENTRY BRANCH

Wednesday, 18th October 1950—Rocket Propulsion and Interplanetry Flight, A. V. Cleaver, A.R.Ae.S.

Wednesday, 15th November 1950—Flutter, H. Templeton, B.Sc., A.F.R.Ae.S.

Wednesday, 13th December 1950—Films.
In the Wine Lodge Hotel, at 7.30 p.m.

DERBY BRANCH

Monday, 6th November 1950—Some Problems of the New Developments in Civil Air Transport Equipment, C. R. Creighton, B.Sc., A.F.R.Ae.S.

Monday, 4th December 1950—Annual General Meeting followed by an " Aeronautical Quiz."
In the Rolls-Royce Welfare Hall, Nightingale Road, Derby, at 6.15 p.m.

HATFIELD BRANCH

Wednesday, 1st November 1950—Methods and Constructions of The de Havilland 106, S. Rudge.

Wednesday, 22nd November 1950—Aviation Medicine, Dr. K. G. Bergin.

In the Senior Staff Mess, de Havilland Aircraft Co. Ltd., Hatfield, at 6.15 p.m.

READING AND DISTRICT BRANCH

Friday, 6th October 1950—Railway Civil Engineering Plant, A. G. Ticehurst.

Wednesday, 25th October 1950—Fatigue, Major P. L. Teed, F.R.Ae.S.

Thursday, 30th November 1950—Car Design and Testing for Quantity Production, A. F. Houlberg, A.R.Ae.S.

At the Abbey Gateway Rooms, at 7.30 p.m.

SOUTHAMPTON BRANCH

Wednesday, 11th October 1950—A Review of Aerodynamic Cleanness, E. J. Richards, M.A., B.Sc., F.R.Ae.S.

Wednesday, 29th November 1950—The Control of Direct Coupled Gas Turbine Propeller Engines, W. H. Lindsey, M.A., F.R.Ae.S.

In the Physics Lecture Theatre, University College, at 7 p.m.

ASSOCIATE FELLOWSHIP EXAMINATIONS RESULTS—PARTS I AND II, MAY 1950

The following were successful in the Associate Fellowship Examinations (New Syllabus) held in May 1950:—

PART I

(HOME)

J. A. H. Bailie, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I; A. D. Balmain, Theory of Prime Movers and Fuels.

G. H. Fenton, Pure Mathematics, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

B. T. Lewis, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

L. F. Nicholls, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

G. S. Pool, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Aircraft Materials and Theory of Structures I.

D. Rowe, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

G. A. C. Searle, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I; P. W. Shaw, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I; J. Sylvanus, Strength of Aircraft Materials and Theory of Structures I.

M. J. Taylor, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

E. G. Wilkinson, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

W. A. Zaremba, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Aircraft Materials and Theory of Structures I, Theory of Machines.

(ABROAD)

W. R. Burge (Canada), Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

A. F. El-Kerdani (Egypt), Pure Mathematics, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

PART II

(HOME)

A. C. Brown, Aerodynamics II; B. R. A. Burns, Aerodynamics II.

D. E. Gladwin, Aerodynamics II.

W. A. Pollard, Aerodynamics II.

A. J. Scarr, Aerodynamics II; H. N. Saint, Aerodynamics II.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).

Grade of membership.

New address (in block letters).

Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

JOURNAL BINDING

The prices of binding of Journals are as follows:—

1949 Volume (including packing and postage), 15s. 6d.

Previous Volumes (including packing and postage), 17s. 0d.

Journals should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the offices of the Society.

Cases only for unbound 1949 Volumes are available, price 6s. 6d. each. Requests for cases, with remittances, should be sent to the Secretary at the offices of the Society.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Robert Elkan Landau (from Graduate), Colin Philip Lindsay Nicholson, William Haughton Pritchard, Basil Ernest Stephenson, John Williams.

Associates

George Whelan Acock, John Bernard Neate Coles, Edward Arthur Dewhirst, Gerald Clifford Frewer, Norman Kearl, Bernard Charles Phillips, Frederick Sydney Staples.

Graduate

Geoffrey St. Quintin Crockett (from Student).

Students

Derek Brickenden, Robert Edward Catterwell, Louis Burton Irving, Edwin John Knight, Brian John Van De Water, John Steele Wright.

ACKNOWLEDGMENTS

The Council acknowledge with grateful thanks the return of back numbers of the Journal from Miss F. B. Bradfield, *Fellow*, and Mr. R. Thompson-Holland, *Student*.

ADDITIONS TO THE LIBRARY

The following have been added to the Library (titles of pamphlets are printed in italics and books marked * or ** may not be taken out on loan):—

American Society for Testing Materials	Manual on Fatigue Testing. American Society for Testing Materials. 1949.
Baker, F. B.	The Performance of Civil Aircraft. Pitman. 1950.

*Brooks, B. T. and Dunstan, A. E. (Editors) — Crude Oils. Chemical and Physical Properties. (Science of Petroleum. Volume V. Part I.) Oxford University Press. 1950.

Hodge, P. G. — Introduction to the Mathematical Theory of Perfectly Plastic Solids. Brown University. 1950.

***N.A.C.A. Technical Memoranda**

1259—*Theoretical investigation on the efficiency and the conditions for the realization of jet engines. Maurice Roy.*

1278—*General solution of Prandtl's boundary-layer equation. W. Mangler.*

1284—*Instrument for measuring the wall shearing stress of turbulent boundary layers. H. Ludwieg.*

1285—*Investigations of the wall-shearing stress in turbulent boundary layers. H. Ludwieg and W. Tillmann.*

N.A.C.A. Reports

920—*The development and application of high-critical-speed nose inlets. D. D. Baals, N. F. Smith and J. B. Wright.*

924—*Application of Theodorsen's theory to propeller design. J. L. Crigler.*

926—*Sound-level measurements of a light airplane modified to reduce noise reaching the ground. A. W. Vogeley.*

931—*Correlation of cylinder-head temperatures and coolant heat rejections of a multicylinder, liquid-cooled engine of 1710-cubic-inch displacement. B. T. Lundin, J. H. Povolny and L. J. Chelko.*

932—*Effect of Reynolds number in turbulent-flow range on flame speeds of Bunsen burner flames. L. M. Bollinger and D. T. Williams.*

936—*Design and performance of family of diffusing scrolls with mixed-flow impeller and vaneless diffuser. W. B. Brown and G. R. Bradshaw.*

940—*The design of low-turbulence wind tunnels. H. L. Dryden and I. H. Abbott.*

A.R.C. Reports and Memoranda

2363—*Antisymmetrical flutter of a large transport aeroplane. W. Prichard Jones.*

2388—*Measurement of mechanical actions by electrical-resistance methods. P. B. Walker.*

College of Aeronautics Reports

36—*Nose controls on Delta wings at supersonic speeds. B. W. Bolton Shaw.*

38—*The profile drag of yawed wings of infinite span. A. D. Young and T. B. Booth.*

Nationaal Luchtvaartlaboratorium, Amsterdam

S.367—*Experimental investigation of the post-buckling behaviour of stiffened, flat, rectangular plates under combined shear and compression. Part III. W. K. G. Floor.*

Publications Scientifiques et Techniques du Ministerè de l'Air

242—*Equations intégrales et transformation de Laplace. M. Parodi.*

N.T.36—*Abrégé de la théorie générale des séries divergentes dite théorie des séries définissables. P. Vernotte.*

O.N.E.R.A.

43—*Essai de justification d'une determination dynamique de fréquences et fonctions propres associeés d'un avion et d'un calcul des masses et des rigidités generalisées correspondantes. A. Schindler.*

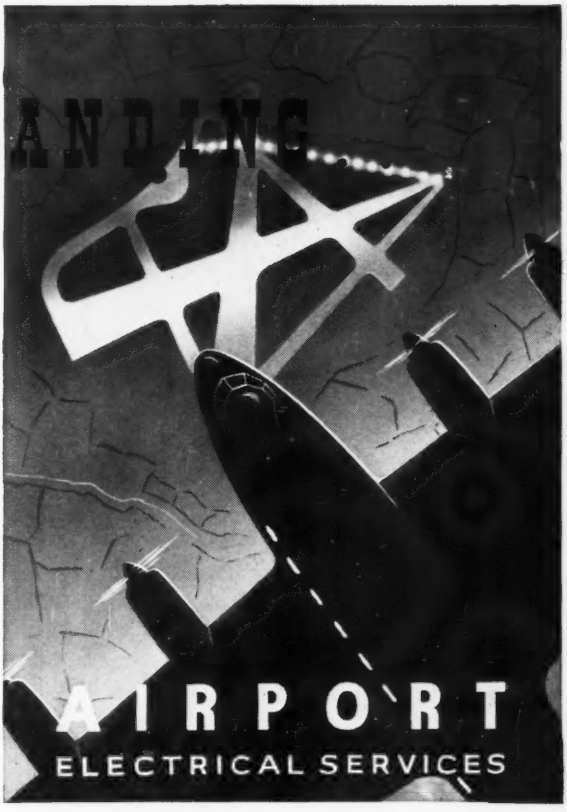
Correction

In the Additions to the Library published in September 1950, under N.A.C.A. Technical Notes 3093—Formulas and charts for the supersonic lift and drag of flat swept-back wings with interacting leading and trailing edges, D. Cohen—the number of this Note should be 2093.

J. LAURENCE PRITCHARD,
Secretary.

Lewes Press (Wightman & Co. Ltd.), Friars Walk, Lewes, Sussex.

HAPPY LANDING



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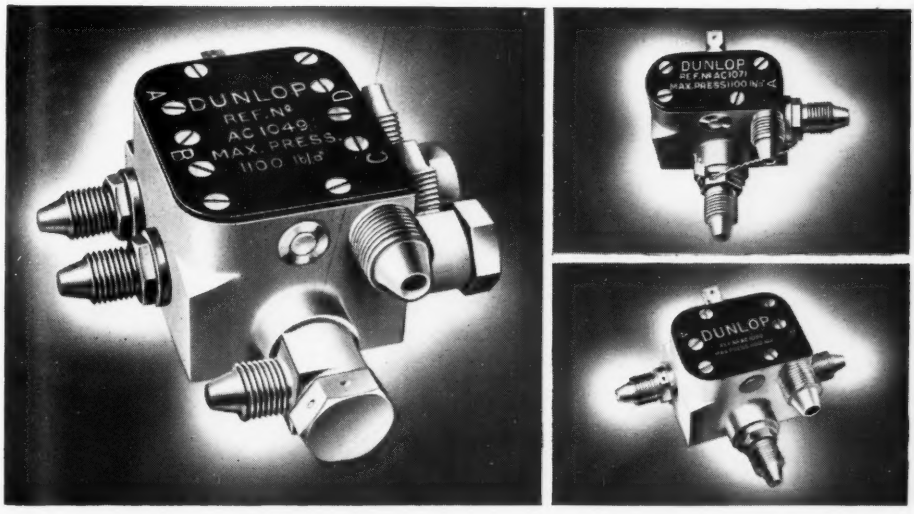

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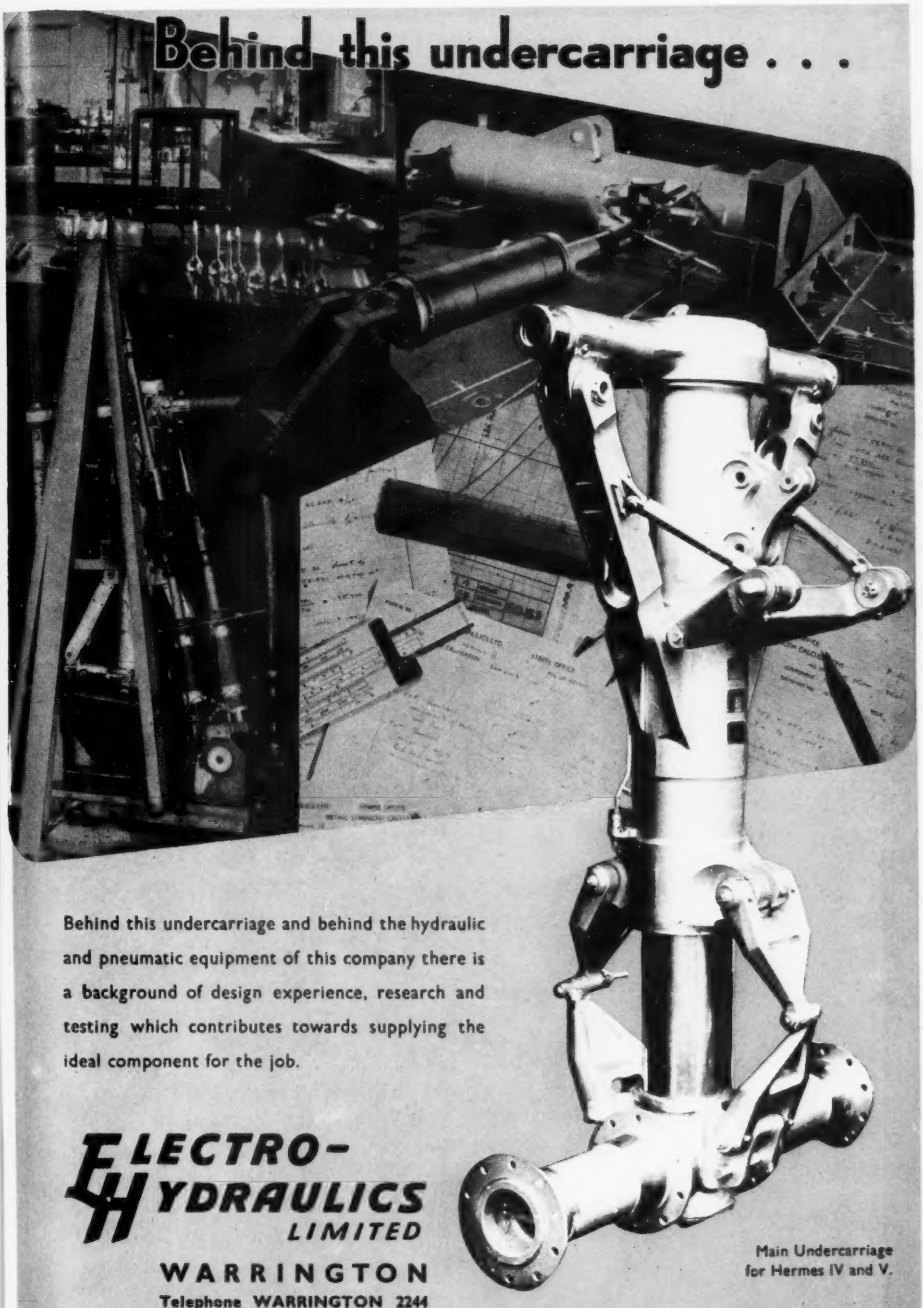

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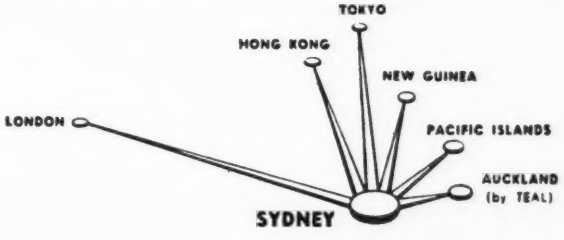

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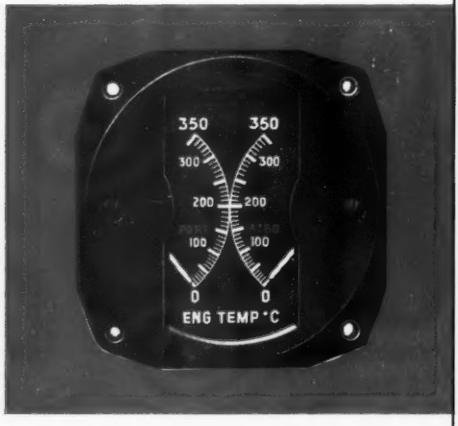

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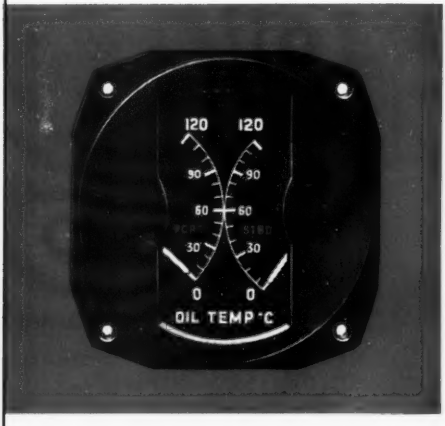

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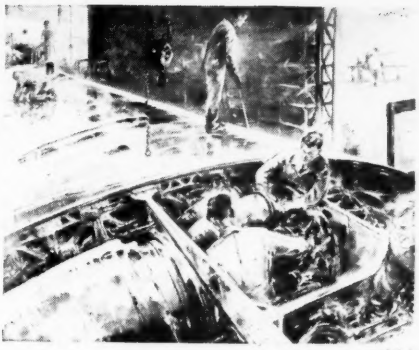

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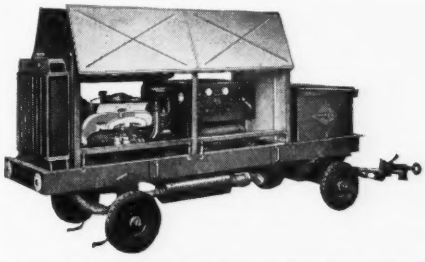

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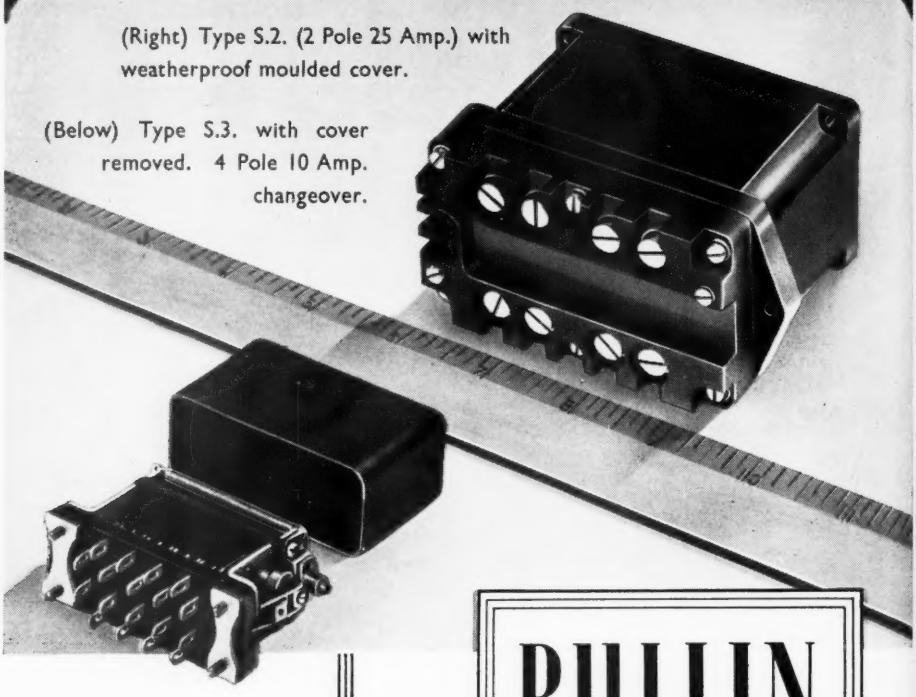

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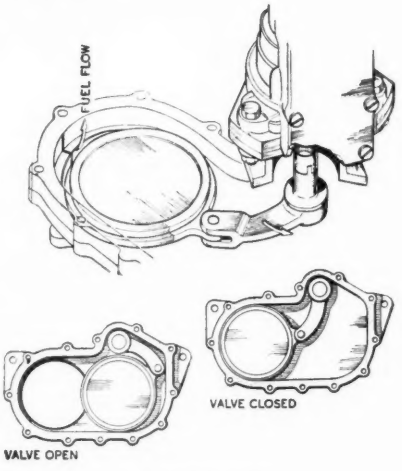

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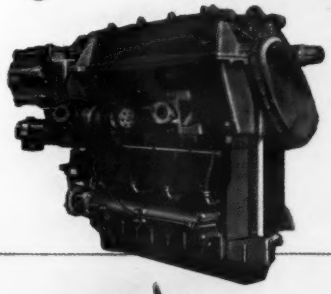

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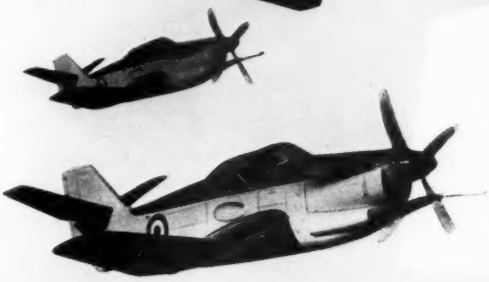

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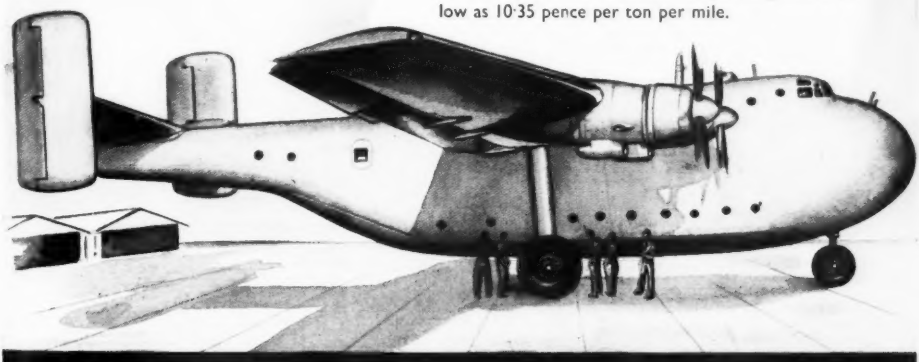

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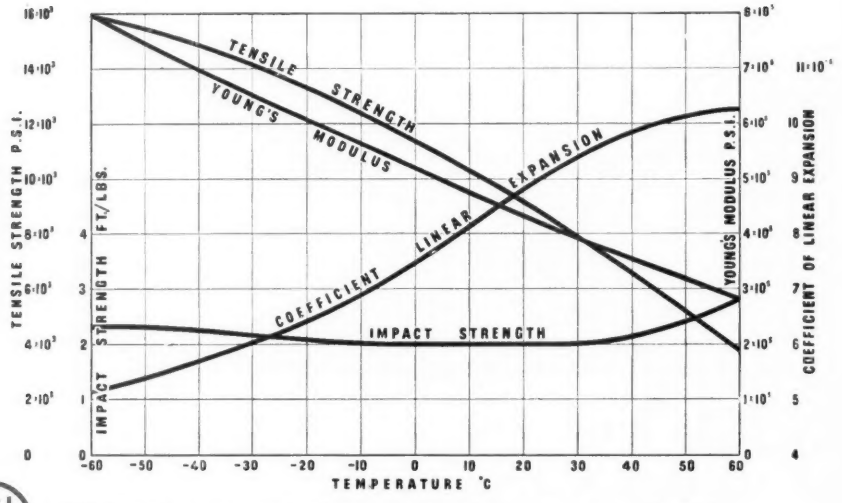

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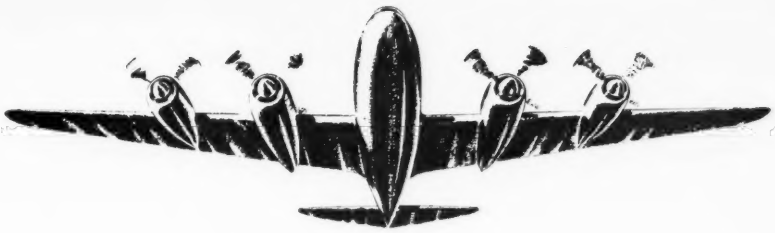

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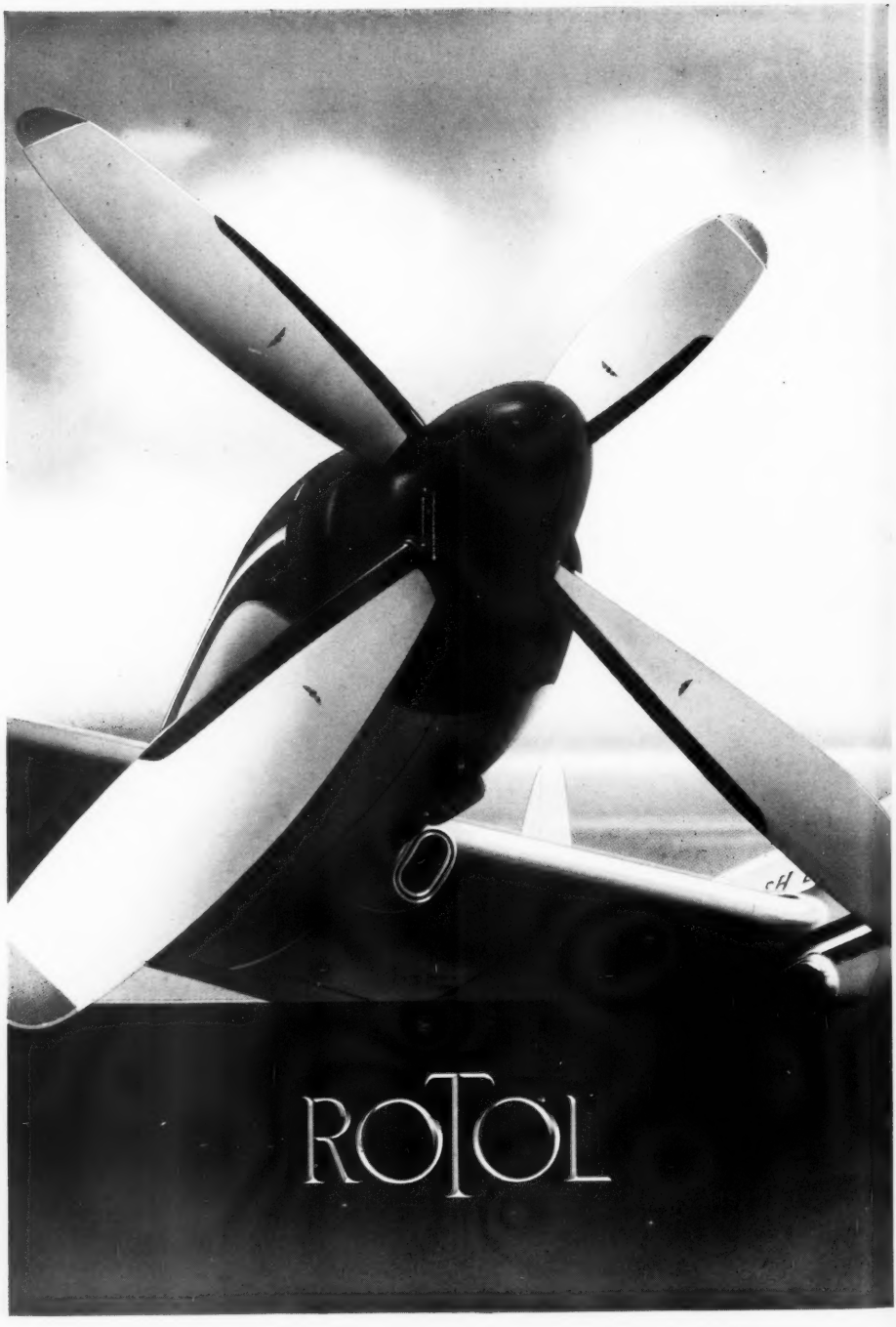
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Only very simple symbols and formulæ should be typewritten. All others should be written carefully by hand in ink. Ample space for marking should be allowed above and below all equations. Greek letters should be designated by name in the margin.

The difference between capital and lower-case letters should be clearly shown; care should be taken to avoid confusion between zero (0) and the letter o, between the numeral one (1) and the letter l, between alpha and a, kappa and k, mu and u, nu and v, eta and n.

All subscripts and exponents should be clearly marked, and dots, bars, and so on, over letters should be avoided as far as possible.

Square roots of complicated expressions should be written with the exponent $\frac{1}{2}$ rather than with the sign $\surd$.

Complicated exponents and subscripts should be avoided. Any complicated expression that recurs frequently should be represented by a special symbol.

Unless an abbreviation is one recognised as standard practice, both in this and other English-speaking countries, for example, b.h.p. for brake horse power, the meaning should be given in full on its first use.

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AIR SURVEY

The Application of Modern Techniques to Surveying and Mapping

by

Professor C. A. HART, T.D., D.Sc.(Eng.), Ph.D., M.I.C.E., F.R.I.C.S.

The 795th Lecture to be read before the Royal Aeronautical Society was given on 16th March 1950 at the Institution of Civil Engineers, Great George Street, London, S.W.1. Sir John S. Buchanan, C.B.E., F.R.Ae.S., President of the Society, introduced the Lecturer, Professor C. A. Hart, T.D., D.Sc. (Eng.), Ph.D., M.I.C.E., F.R.I.C.S., Professor of Surveying and Photogrammetry at University College, London. Professor Hart was the first Professor of Surveying and Photogrammetry to be appointed in the British Commonwealth and was leaving almost immediately for India to become Vice-Chancellor, University of Roorkee, United Provinces.

1. INTRODUCTION

THE employment of aircraft for surveying has become so usual, and so much has been written about it from one aspect or another, that perhaps the time is appropriate to define exactly what is meant by Air Survey; what the surveyor is trying to achieve, and how he is dependent upon the airman to obtain his objectives. To achieve good results from an air survey, closely integrated team work is required. The airman, photographer, instrument specialist, meteorologist and the surveyor each depend upon the other, any weakness in the chain making results more expensive and less effective. The author, as a surveyor, has worked in harmony for a good many years with the "air" side, and it is proposed in this paper to summarise the surveyor's approach and his requirements, and to explain why he seems never to be satisfied with the accuracy achieved. The greater the accuracy of photography, the simpler, quicker and cheaper become methods of using the results to fulfil the desired specification.

Air survey implies neither merely the taking of air photographs, nor solely the production of maps from them. The definition must include all uses of aircraft for mapping; for indirect measurement of long lines on the earth by radar methods; for reconnaissance in undeveloped countries, and for geological and geophysical surveys.

In recent years there have been in successive generations two outstanding events in the development of surveying, both resulting from progress in aeronautical science.

The first was the introduction of practical air photography in the 1914-1918 War, by which not only were areas inspected for intelligence purposes, but also topographical details provided from which quite reliable maps could be made. Since then such progress has been made that no one can now fail to be aware of the importance of air photography for map-making.

The second advance arose similarly from war-time needs, following successful application of radio and radar aids to navigation. It was thought that perhaps here was the solution to a problem which had perplexed the surveyor, *i.e.* the taking of air photographs with the position of the aircraft accurately "fixed" in space in relation to the surface of the earth, so as to provide map control which previously had to be surveyed on the ground. In 1943 a survey camera and some ancillary equipment were fitted during the operational trials of "Gee-H" (a well-known radar aid) and despite the crude arrangements, remarkably good results were obtained. Following a visit to South East Asia, the possibility was brought to the notice of the Chiefs of Staff, and the necessary

investigations were given adequate priority. By use of these navigational aids, important developments have ensued in mapping and geodetic surveying.

During the period of evolution many new techniques and instruments have been evolved and developed, and British scientific technical skill has been well to the forefront, although one must state regretfully that in some cases, most of the fruits of this work have been lost to the country by official "laissez-faire"—or maybe official higher priorities!

Air survey has now "come of age" in the technical sense, and is accepted not for its own sake, but as a means of providing data required by surveyors.

The subject of this paper is vast, embracing most of the modern approach to surveying, and the paper, therefore, is in the nature of a general review. Academically, surveying has received recognition through the creation in 1946 of the first Chair in Surveying and Photogrammetry in the Commonwealth at University College, London, to which the efforts of Sir Alexander Gibb, Mr. Colin Williamson and Professor H. John Collins contributed in no small measure.

2. THE SURVEYOR AND DEVELOPMENT

Before what may be called the "air age" of surveying, the tempo of economic exploration of undeveloped countries was slow, largely due to the inability of map makers to move rapidly from place to place when priorities changed, and provide maps of areas where they were wanted without undue delay.

The acceptance of air methods and their development through research has resulted in a complete revision of our conceptions of the speed and effort necessary for surveys, particularly in inaccessible and undeveloped areas. The Land Surveyor can now, with the aid of the airman, speedily fulfil the requirements of modern development. No longer is it a recognised practice to make *ad hoc* surveys for specific jobs, with little or no likelihood of assimilation to the national mapping system. The modern land surveyor (defined by the altitude of his product, rather than that of his picture platform!) has something to offer which brings him to the forefront of schemes for economic and cultural development, and puts him on a basis of direct co-operation with all those concerned with scientific and economic development. Previously the value of good maps, by virtue of the time-lag between requirement and production, was something of a hidden asset. Maps were useful if they were available, but the long-term value of their preparation to the community as a whole was rarely recognised, at the time when the work should have been initiated. It is unfortunately true that frequently transient political aspects have resulted in the surveyor being the first to feel the draught of retrenchment. The advantages of increased speed and eventual overall economy of the use of air methods have often been over-shadowed by the high initial cost, whereas the greater actual cost through spread-over of departmental expenditure has not been realised.

Generally, one can now say that there is every indication that short-sighted economies in national mapping programmes are less likely than before and vast programmes are in hand, for example, at home by the Ordnance Survey, in the Colonies and the Dominions.

Expenditure on national surveys is comparatively small, but has an investment value far beyond its initial cost in efficient long-term development. Even in this highly developed country, the effect of unwise economies between the Wars, causing the national plans to fall very much out of date has complicated the present urgent problems of mapping.

In backward countries, with poor communications, surveyors would make journeys into the "bush" and spend several months away from headquarters. It was difficult to "switch" priorities, because of the time factor, and therefore the survey department had an almost impossible task when priorities changed. As an example: in one Colony where, after a good many years, only about fifteen per cent. of the country was covered with 1/100,000 maps, radar control has enabled large areas to be covered with provisional 1/100,000 maps with little ground control.

In areas such as North Canada and Central Australia radar ranging from the air is enabling control to be established rapidly as a basis for reconnaissance and topographical mapping.

At present the efficacy of air survey to large scales for engineering and similar surveys is becoming more recognised as photography, photogrammetric instruments and plotting techniques improve.

Air photographic reconnaissance coupled with the employment of geophysical methods, often gives an indication of physical structure, as well as topographical form to localise areas worthy of close inspection.

3. THE SURVEY PROBLEM

In making a map or plan, the surveyor must obey certain fundamental rules. He must work from "the whole to the part," since in mapping an area, it is important that the map sheets should fit together. His framework is a primary triangulation survey by which he establishes a limited number of points accurately in relation to each other and to the earth. This is broken down into secondary and tertiary triangulations and the topographical detail is finally filled in to make the map. For the detail stage in the past, plane-tabling was generally used, but is now largely superseded by air photography, which enables a similar process to be carried out in the office. The survey design must be coherent, especially when one wishes to fit independent surveys together. During the War, for example, owing to the complexities of various national surveys, much trouble was caused by a discrepancy of some four miles in Central Europe, and in one early effort in assembling independent surveys in South Africa, blank areas had to be labelled "These areas do not exist."

Therefore, the surveyors must have a rigid framework which is still generally provided by field surveyors, although air survey is increasingly able to reduce the amount of ground work—particularly if radar methods are used—while for geodetic surveying, where wide gaps must be bridged, the new methods of radar ranging are proving invaluable as a means of providing a reasonable accuracy with much greater speed.

In triangulation in the past the triangles were established by angular optical measurements, the sides being generally not more than 100 miles in length, scale being fixed by measured base-lines, and orientation by astronomical observation. Radar methods now enable sides of 500 miles or so to be measured directly with considerable accuracy.

Surveying from air photographs presents problems which have no direct solution, and the surveyor must attempt to achieve the accuracy which his task demands since, like the engineer, he works to a specification. The method employed for a particular task should be the most efficient and economical for the purpose at hand, coupled with fulfilment of long term policies. Thus for many purposes maps can be made from air photographs by what is known as the "radial line" method (Fig. 1) where each photograph is used as a plane-table station, and there is a geometrical connection between alternate photographs. This often excites adverse comment from continental surveyors who stress and claim advantage for the greater accuracy which can be obtained from automatic plotting machines. Academically, generally they are correct, but if an accuracy of, say, three feet is sufficient, and can be obtained efficiently by a simple method, what is the use of undue elaboration to obtain an unrequired accuracy of three inches? That has always been the essence of the British approach in air survey.

If the photography is perfect—*i.e.* there are no distortions due to lens or photographic materials, or obstruction due to haze or cloud —then the photograph presents a true perspective picture. Thus, if an air photograph is taken truly vertically over completely horizontal ground, the result is a true plane. There are, however, two main difficulties: (*a*) inclination or "tilt" of the axis of the camera from the vertical, and (*b*) variations of ground height, both resulting in distortions of photographic images from the position they would occupy in a true plan.

The basic geometrical relationship of a pair of photographs is illustrated in Fig. 2.

The effect of tilt is to present an oblique view and to cause variations of scale over the photograph. This effect can be seen by holding a circular plate squarely before the eyes, when it appears as a circle. If, however, it is rotated about a diameter it appears elliptical and eventually becomes a straight line when the "tilt" is 90°.

Unfortunately, no one as yet has succeeded in defining the vertical accurately in the air, and for aerodynamic reasons, tilts cannot yet be reduced to limits which render them insignificant to the surveyor. For accurate mapping, the surveyor has to make photogrammetric observations for precise determination of tilt.

Height distortion is important. If a vertical factory chimney is seen from, say, the top of a hill, both the top and bottom will be seen, although in plan these would coincide. This is height distortion, apparent in nearly every air photograph.

For simple plotting at medium scales, it is possible to assume that angles measured from

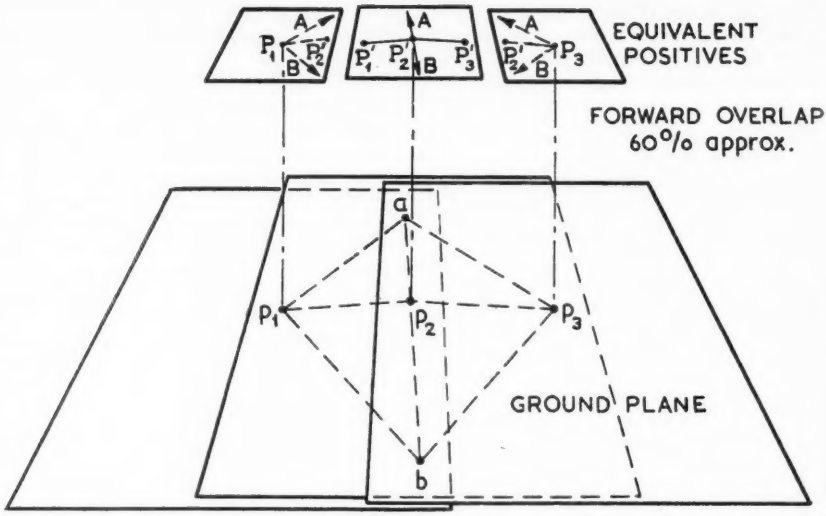
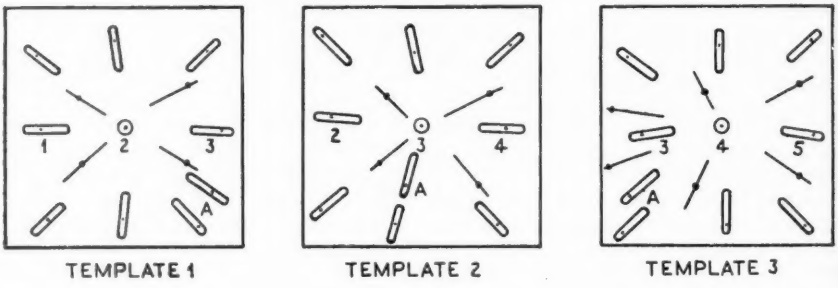


Fig. 1*a*.



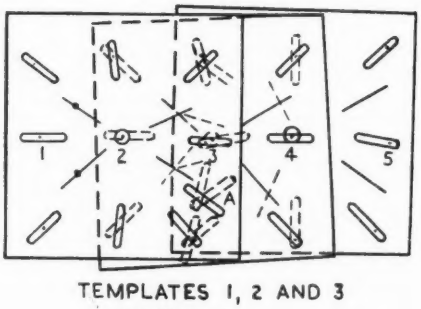


Fig. 1*b*.

Fig. 1.
Radial line assembly by slotted templates.

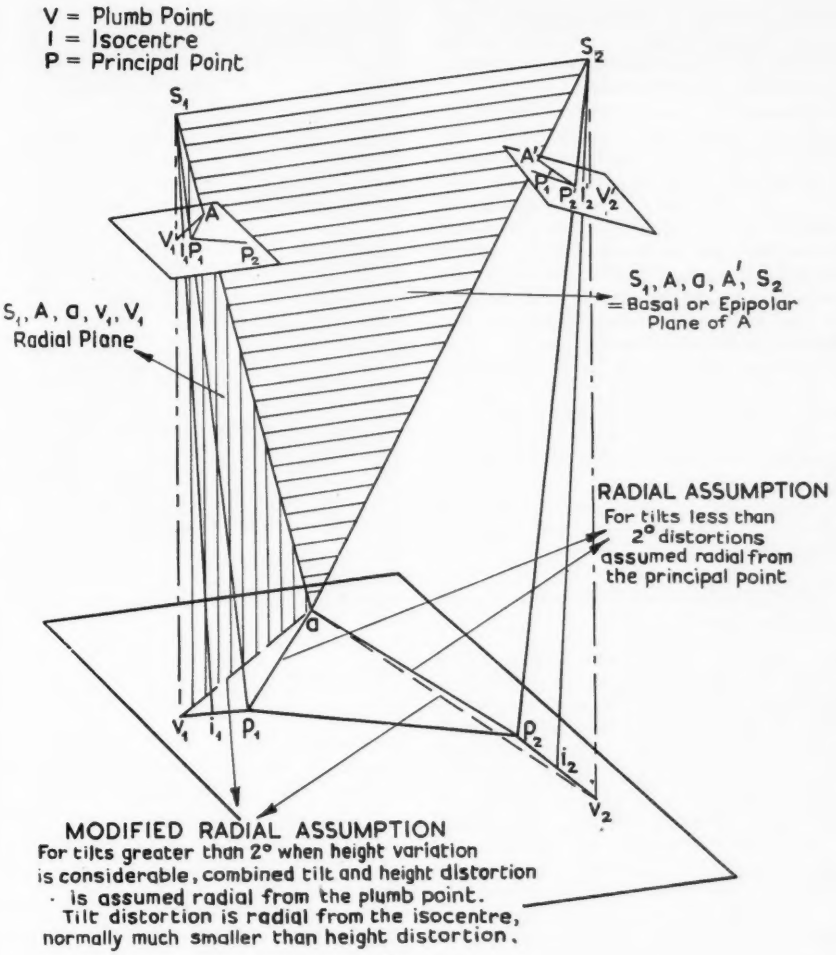

V = Plumb Point
I = Isocentre
P = Principal Point
S1
S2
A'
P1 P2 I2 V2
A
V1 I1 P1
P2
S1, A, a, A', S2
= Basal or Epipolar Plane of A
S1, A, a, V1, V2
Radial Plane
RADIAL ASSUMPTION
For tilts less than 2° distortions assumed radial from the principal point
a
V1 i1 P1
P2
i2
V2
MODIFIED RADIAL ASSUMPTION
For tilts greater than 2° when height variation is considerable, combined tilt and height distortion is assumed radial from the plumb point.
Tilt distortion is radial from the isocentre, normally much smaller than height distortion.

Fig. 2.
Geometrical relationship of a stereo-pair of air photographs.

the centre or principal point of the photograph are correct and this gives rise to the radial line method of plotting (Figs. 1 and 2), but when great precision and larger scales are involved, we must take cognisance of the fact that height distortions are radial from the plumb-point which is vertically below the camera lens at exposure, and that distortions are arising from scale changes due to tilt from another point called the iso-centre.

Therefore, for certain classes of precise work the surveyor is forced to a "three-dimensional" approach, whereby the photographs are set in their correct relative positions as at exposure. The exact geometrical solution is provided by employment of what is known as the "epipolar" or "basal plane" principle. In Fig. 2 the point "a" in the datum plane has two photographic images A and A^1 on the first and second photographs respectively. The five points S_1, A, a, A^1, S_2 form the basal plane, S_1 and S_2 representing successive positions of the camera at exposure and providing the air-base. It can be shown mathematically that if five such pairs of photographic images are set in their correct basal planes, the photographs are correctly

orientated. All three-dimensional stereoscopic plotting machines, most of them costing thousands of pounds, are designed to enable this condition to be satisfied.

In the ordinary way, the position of the aircraft in space is not known, and the absolute altitude is known approximately only from altimeter readings. The data therefore provides no means of establishing (*a*) accurate scale, (*b*) tilt, unless reference is made to fixed points on the ground. These points are known as "ground control." The big advance made by the employment of radio and radar aids, apart from improved navigation, is that the aircraft position can be fixed in space and, by accurate navigation, the photographs can be so linked together that their tilts can also be determined with some accuracy. This provides the necessary information for map making under certain conditions, without recourse to the ground other than that at radar ground stations, which can be 200 miles or more from the photographic area.

4. MODERN DEVELOPMENTS IN AIR PHOTOGRAPHY

The ideal of air survey photography, unfortunately unrealisable, is that the photographs should be taken vertically, at constant altitude, in strips exactly where required, with stereoscopic overlaps just sufficient to carry forward the survey triangulation along the strip and with lateral overlaps to enable the strips to be connected together. The nearer the ideal conditions can be fulfilled, the simpler becomes the surveyor's task in providing a desired standard of accuracy.

It is not proposed to discuss the navigator's problems, which have been dealt with in particular by Saffery* and others, but rather the effects of departure from the ideal upon the survey as a whole and to consider the effects of employment of electronic aids.

With good manual navigation, tilts can be kept down to 2° and course maintained accurately enough for many purposes but the accuracy of aircraft courses is increased and tilts reduced by employment of an automatic pilot. Attempts have been made to measure relative tilts by gyro-controlled artificial horizon, and relative tilts were found to be determinable to about half a degree, but occasional random errors of much greater magnitude so far make it inadvisable to dispense with photogrammetric analysis.

Fig. 3.
Installation of Williamson O.S.C. camera in Anson aircraft of Air Survey Co. Ltd.

Precise gyro-stabilisation of camera mountings is still unrealised, but experimental work now in hand at the Royal Aircraft Establishment is promising.

The surveyor wants accurate perspective depiction of the photographic image to within his own limits of measurement, thus the survey camera should be designed as a *survey instrument*, with the lens, non-distorting shutter, cone and register glass (if fitted), all built and calibrated as a unit. Such a camera is the Williamson O.S.C. film camera (Fig. 3) with a format 9 × 9 inches, six-inch Ross wide-angle lens, and instrument records on the side of the main film.

The flying of a block of survey photographs involves considerable expenditure of flying time, photographic materials, and employment of photographic staff, and much technical effort is required from the surveyor before the final map can be produced. It is essential therefore to ensure that the most satisfactory photographic materials are

* Saffery, J. The Navigator's Problem in Air Survey. Jour. Inst. of Navigation, Vol. 2, No. 3, July 1949.

employed and subsequently processed with great care to ensure minimum distortions.

For large survey projects it is generally necessary to use film and the best results are obtained by using topographical-base film developed without stress, and dried very carefully under conditions which ensure minimum distortion.

Under properly controlled conditions, the ultimate differential distortions on topographical film base do not exceed 0.01 to 0.02 per cent., which is quite adequate for all but large-scale work, or where it is required to bridge across several photographs without ground control.

Reduction of image distortion is always important and since, in practice, in many cases it is economically desirable to use a lens which gives as wide a field as possible (about 95°) there are inherent distortions due to design, which have to be reduced before use is made of the photographs. For example, in Multiplex working (*see* Fig. 10) miniature diapositives are made on lantern slides from the original film by means of a reduction printer designed in conjunction with the survey camera and projector lenses so that the projected image is distortion-free. In one precise three-dimensional measuring instrument, the Wild Autograph A5 (*see* Fig. 12) a special refracting plate is inserted in the optical viewing system to correct the image positions or, alternatively a correcting printer is used to make positive transparencies with distortions eliminated.

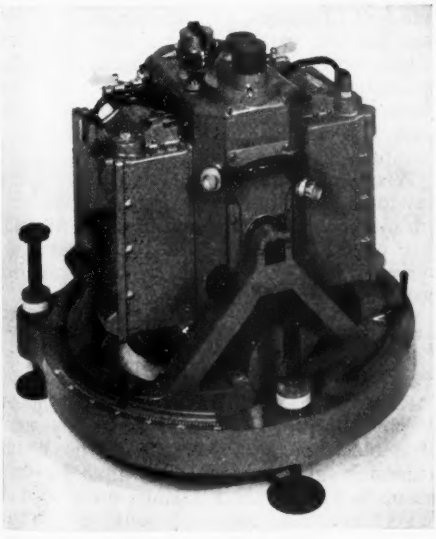


Fig. 4.
Wild R.C.7 automatic plate camera.

In cases where co-ordinate measurements are made in a precise stereocomparator, the prints are made on a non-distorting surface such as sensitised aluminium foil, corrections being applied from a distortion chart appropriate to the camera.

The fact that the surveyor can sometimes "make do" with less accuracy does not mean that he is by any means satisfied, since the better the photography, the higher can be the survey accuracy, simpler plotting techniques may be used and less ground control is required.

A considerable advance in air photographic technique for accurate large-scale mapping has been achieved recently by the introduction of the Wild R.C.7 automatic plate camera using glass plates and fitted with the new Aviotar lens (Fig. 4). This camera has a magazine of forty plates and automatic plate-changing device. The lens, with a field of 60°, is virtually free from distortion and has excellent resolving power.

The present position therefore is that if air photographs are taken with due care and suitable aircraft and cameras, the surveyor's requirements can be satisfied as regards accuracy, but his techniques still require to solve the unknown factors of tilt and height of aircraft, not yet provided accurately enough for him by the airman to satisfy all requirements.

5. THE PRINCIPLES OF ELECTRONIC MEASUREMENT

The application of electronic measurement to surveying has become possible because of the precision of the frequency of radio transmissions and the accuracy with which the time of transmission of signals may be measured. As an indication of the precision obtainable the D.S.I.R. began experimental standard frequency transmissions from Rugby on 1st February 1950, monitored by the N.P.L. to within two parts in 10^8. (*Times* 4.2.50).

Two methods have so far been used for survey measurements.

(*a*) Radar, which is simply a method of superimposing pulsed signals on radio waves, so that accurate times of transmission of signals are measured.

(*b*) Phase-difference of continuous-wave radio whereby positions may be fixed by measuring the difference of phase from two pairs of stations, if a starting point for calibration is known. The Decca Navigator works on this principle.

Surveyors have made use of these techniques as follows for:

(*i*) Strip navigation;

(*ii*) Fixation of an aircraft in space in relation to remote radar controlling stations at the instant of exposure of an air photograph;

(*iii*) Measurement of long lines on the earth.

The method used has been mainly the radar method of instantaneous range measurement synchronised with photography from the aircraft to two accurately located ground stations (Fig. 5). The aircraft is flown along a circular track at constant range from one station. Range measurements from the second or rating station are used when photo-positions are required to be fixed. Charts are constructed which consist of range circles concentric with two stations (Fig. 6*a*).

Alternatively a hyperbolic system of navigation may be used (Fig. 6*b*). The "Gee" system of radar navigation has no particular application for survey. The Decca Navigator, which is having increasing survey applications, is a low-frequency continuous-wave system, also operated from a master and two slave stations. Positions are fixed by the intersection of lines of equal phase-difference from the two stations, and these lines enclosing the lanes are similarly hyperbolic. It appears so far, that the actual accuracy of navigation at similar ranges may be of the same order as the radar method and in some cases for relative spacings, better. It is perhaps not quite so convenient as the "circular" systems for arranging flying programmes, but on the other hand, ranges may be recorded up to 1,000 miles,

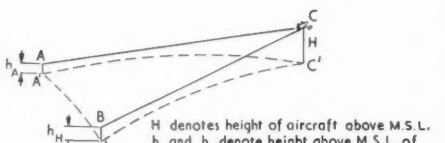


Fig. 5.
Radar fix.

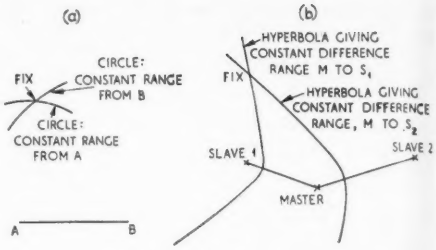


Fig. 6.
Circular and hyperbolic systems for obtaining fix.

although with rapidly decreasing accuracy. It can also be used for hydrographic surveys and for fixation of ground points when free from local interference, since the optical range condition is not necessary as it is for radar with frequency high enough for accurate survey measurement.

For single radar range readings the total probable random error is about ± 50 metres for the Gee-H type of equipment with a wave length of 7-10 metres, and about ± 20 metres for "Oboe" or "Shoran" with wave lengths of about one metre or less. The latter can be reduced to 5 metres under static conditions.

The high frequencies used for radar measurement are effective only within the optical range. For air survey it is generally sufficient to assume a mean rate of propagation for the particular conditions, but the requirement is much more stringent for static observations, and careful data must be gathered about atmospheric conditions and correction applied accordingly to allow for variations in the rate of propagation.

When low-frequency systems are employed, day-to-day variations of propagation velocity are marked and are difficult to allow for and this affects application of the system for survey fixes, although local relative accuracies can be very high.

6. SURVEY NAVIGATION BY ELECTRONIC METHODS

Radar navigation for controlling photography has proved effective since any part of a block of photographs may be flown accurately at any convenient time by this means. The method mainly used so far has been that of instantaneous range measurement by radar, simultaneously with photography, from the aircraft to two accurately located ground stations, or vice

versa. Knowing the location of the stations, the two slant-range measurements, and the approximate altitude, the position of the aircraft may be determined in relation to the earth's surface. Also, the ranges for a particular position may be pre-determined, and the aircraft navigated to that position for an exposure. The aircraft is flown along a circular track at a constant distance from one station and approximate range readings from the second station determine the beginning and end points of the strips. The overlaps may be matched laterally where this is desired. Alternatively, for stripping, one radar station is sufficient if there is adequate detail mapped for identification of terminal points. The one-station method has been used over considerable areas of the African Colonies.

When no suitable maps exist the ground stations may be plotted on a blank graticule and the range for each strip determined, first by selecting an arbitrary starting range, and subsequently, by computing the radar range difference for the required lateral overlap. When the aircraft is following the required track in the case of "Gee-H" (which has ben most frequently used), the corresponding reading shows on the cathode ray tube, but it is advantageous to couple an aural signal to the pilot to indicate "on" or "off" track.

A flying programme is prepared giving track readings and also individual ranges for each photograph from the second station if fixation is required as well. The aircraft is brought on to track and steadied before the beginning of each run and to establish fix, the reading of a second cathode ray tube may be recorded on an automatic observer (Fig. 7) at the instant of photography.

Gap-free blocks have been flown consistently even when strips are flown on different sorties. As examples of experiments which established the use of radar, air photographs of Anglesey were taken from "Gee-H" stations, 160 and 110 miles away respectively, at a scale of 1/54,000 with a six-inch lens, the maximum variation of overlaps both laterally and longitudinally being ± 4 per cent. from those specified (Fig. 8). The flight plan of a series of control strips similarly flown in the neighbourhood of Norwich, with the same camera, at a scale of 1/28,000 gave a maximum variation of overlap from standard of ± 6 per cent., which is more accurate in actual distance owing to the larger scale.

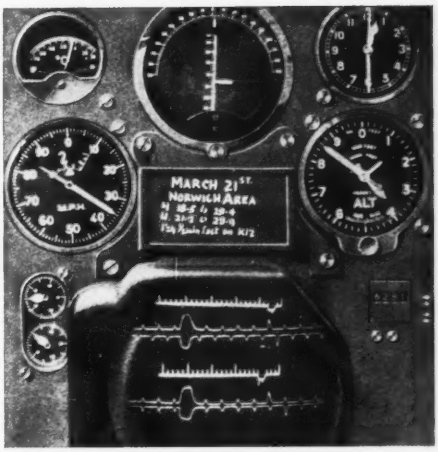


Fig. 7.
Automatic observer record.

Greater accuracy was obtained with the more complicated "Oboe;" with a similar camera and photo-scale of 1/17,500 the maximum variation of overlap was ± 5 per cent., or three times the Anglesey accuracy.

The effect of such control is that for photography at 1/20,000 the specified lateral overlap may be cut to about 15 per cent. with certainty of complete cover, as against 25-30 per cent. under ordinary conditions.

No particular difficulty has been experienced in dealing with strips flown on a curved track of not less than about 30 miles, but straight line tracking would be an advantage in stripping with the run of the topography, and it is anticipated that this will be possible in the near future by a straightforward technique. In any case the economy of photography is considerable, but comercially so far the cost of the equipment is too high, unless it has an alternative use.

An important advantage of radar navigation and fixation of air photographs is that when it is necessary to avoid delays in the preparation of the map, the flying programme may be computed geodetically, and the actual positions will be found to correspond closely enough to allow of simple interpolation for the absolute fix.

An example of a portion of a Decca Navigator lattice chart is given in Fig. 9*.

* Miskin, E. A. Air Survey Equipment. British Engineering, Vol. 32, No. 51, December 1949.

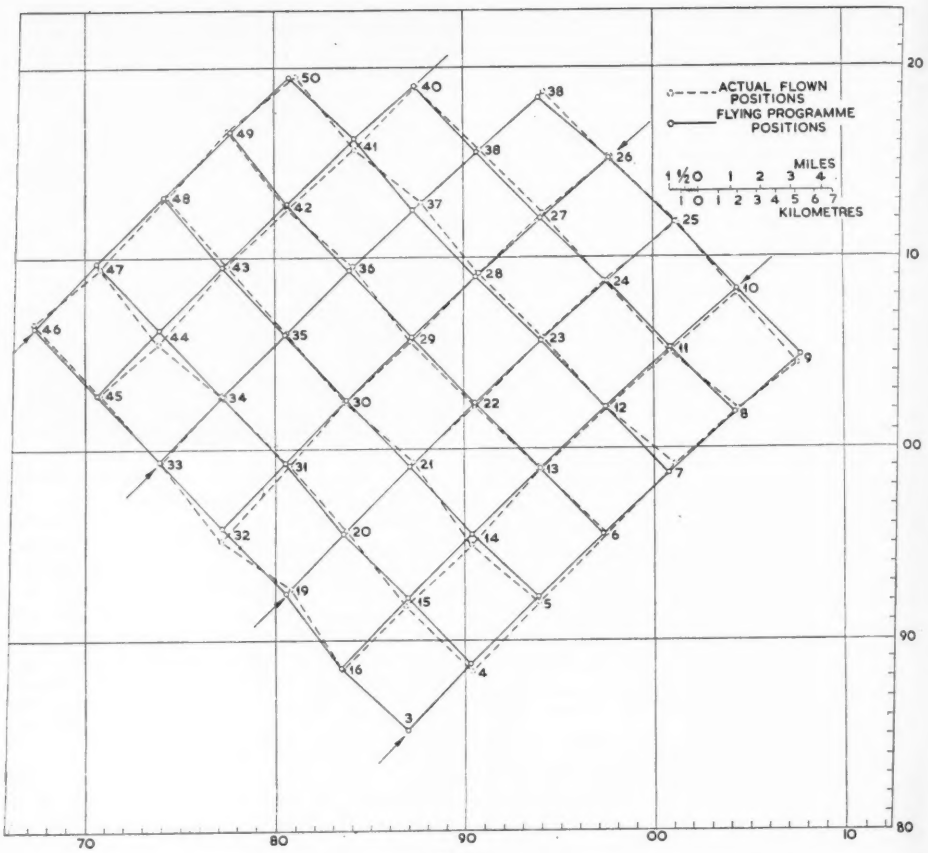


Fig. 8.
Anglesey block of radar controlled photography. Test G.H. 2/6 Anglesey.

The readings are made on Decometers, as shown in the inset. These can be photographed in an automatic observer synchronously with air photography or used for tracking. The dials record "phase-difference," but by setting at a known point the absolute position can be determined.

This system is proving of value for strip navigation and relatively, it is more accurate than the radar methods, despite day-to-day anomalies in propagation rates due to the effect of atmospheric conditions on the long-wave lengths of 3,000 metres or so. It can be used advantageously where a Decca Navigational Chain has been installed. Tracking is either effected by flying along a lattice or lane direction, or by a navigational plotting technique along a straight line.

As an example of the effectiveness of this system the Ordnance Survey now specify Decca Navigation for some of the photography which is done for them by the Royal Air Force*. As an example, photography at 1/2,500 scale with a 20-inch lens for 1/1,250 Town Re-Survey where the distance between flight lines is only 250 yards, and where small tilts and deviations can result in serious loss of overlap. In a comparison which was made between visual and Decca Navigation, about 2½ times as many photographs were required to cover a given area effectively by visual navigation as with Decca Navigation. It was found that whereas 64 Decca-controlled photographs were needed a

* Information supplied by D.G.O.S.

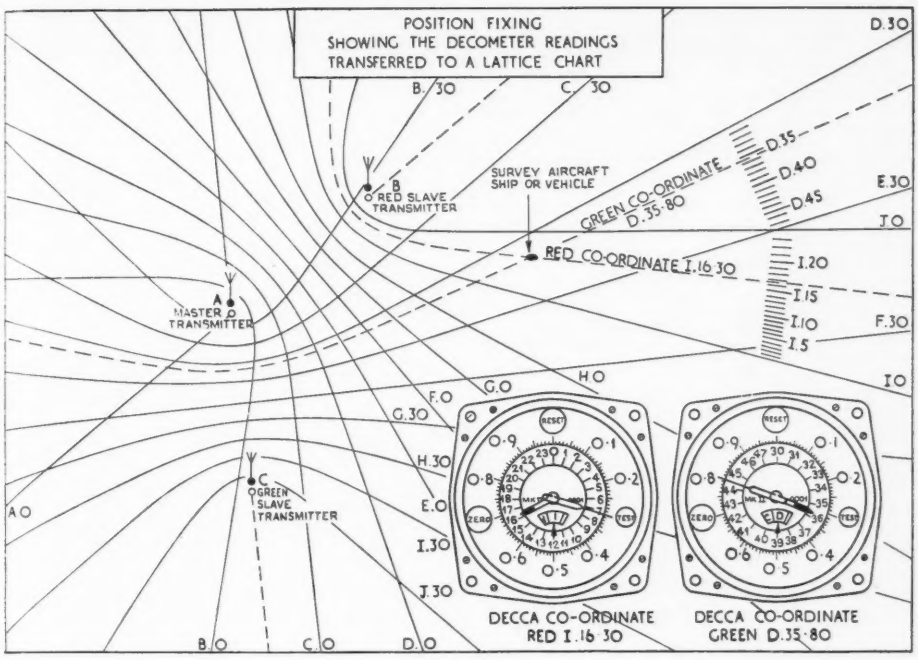


Fig. 9.
Decca Navigator chart and decometers.

square mile, often as many as 150 were required with visual navigation. One area of 35 square miles in Central London was flown with Decca control, without any gaps in lateral overlap. The uniformity of flight lines makes their recording much simpler.

The object is to fly parallel straight lines along the lanes at a constant overlap, and provided that the strips are kept short enough to avoid sensible variations due to changing width of the Decca lanes, it is clearly established that the R.A.F. is enabled to provide much more accurately than before, the strip photography required by the Ordnance Survey for their new large-scale plans.

It may be mentioned here that the Decca Navigator Co. have developed a light-weight Survey Chain, whereby the ground stations are much more easily transportable than before, so that the system can be effectively used in undeveloped countries or other areas where there is no ordinary navigational chain.

Navigation in strips of the order of accuracy described, enables the surveyor's requirements to be more nearly satisfied and, with accurately flown strips, his methods of plotting can be simplified and his accuracy increased.

7. METHODS OF MAP-MAKING

The two basic methods of mapping, namely the "radial line" and "basal plane" have already been mentioned. Generally speaking, in this country for topographical mapping and where tilts can be limited to 2° or less and ground height variation is not more than 10 per cent. of flying height over an overlap, the radial line method is used for plan, generally now by the mechanised process known as the "slotted temple" method (Fig. 1*b*), where slotted templates are cut and fitted together so that the radial lines intersect at the common points used to carry forward the photo-triangulation. Unless there is adequate ground height control on each overlap, however, the process of contouring is laborious and not very accurate, although there are several quite good methods for producing form lines. For production of contours, the basal plane principle is usually employed, and for this

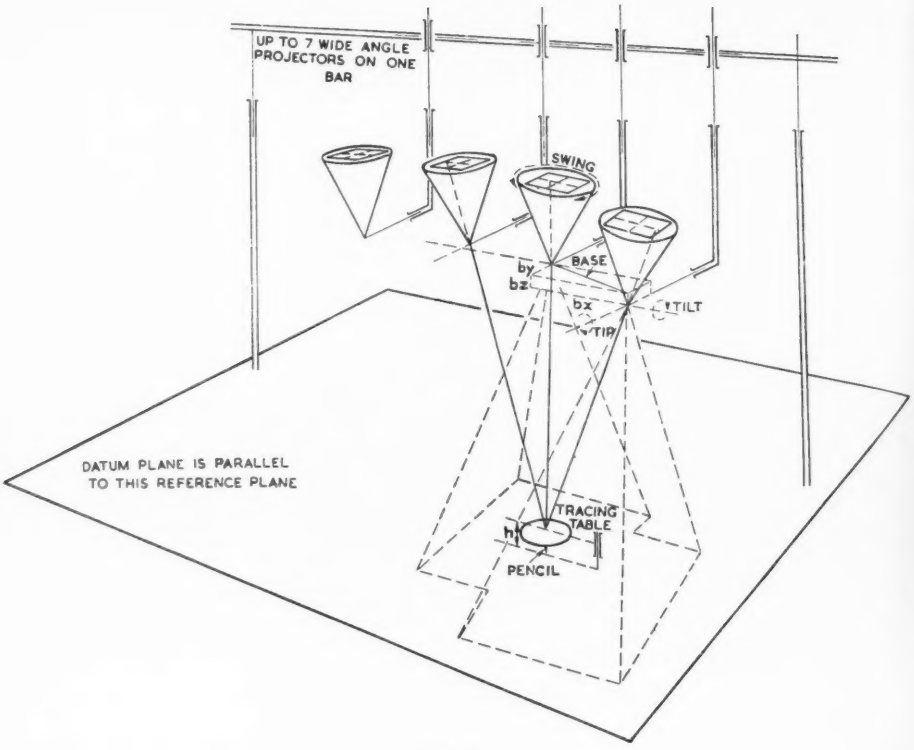


Fig. 10.
Principle of the basal-plane as applied to the Multiplex method.

purpose the "Multiplex" method is adopted; and quite frequently it is used for the whole process of mapping. The principles are illustrated in Fig. 10 (*see also* Fig. 2). Small glass diapositives of each photograph are inserted in projectors and the image projected through a red or green filter. A stereoscopic pair so projected, one through each colour, and set by adjustment in correct relative position, gives a three-dimensional impression when viewed through a pair of spectacles, with complementary green and red filters respectively. The model can be set to scale either by reference to plotted ground control or to a previously drawn slotted template plot. It is also possible to plot detail and contours along a strip of photographs by this method. The Williamson-Ross S.P.3 equipment (Fig. 11) is being used in Great Britain, in the Commonwealth generally and in many other parts of the world.

When it comes to precise large-scale mapping, air survey can often compete with ground methods only in special cases and particularly where access is difficult, or where the time-factor is important; nevertheless the availability of photographs for continuous inspection and other methods is increasingly making its use a sound proposition. Here, except perhaps where there is dense control and where contours are not required, the radial line approach must be abandoned and resort made to photography on glass plates and use of precise three-dimensional plotting machines, such as the Wild Autograph A5, the Poivilliers-S.O.M. Stereotopography or the Santoni Aerocartograph. The Wild instrument, for example, is in operation in Great Britain at present, at the Ordnance Survey, Hunting Aerosurveys and University College, London (Fig. 12). For large-scale surveys it is always necessary to make some measurements on the ground, and as an

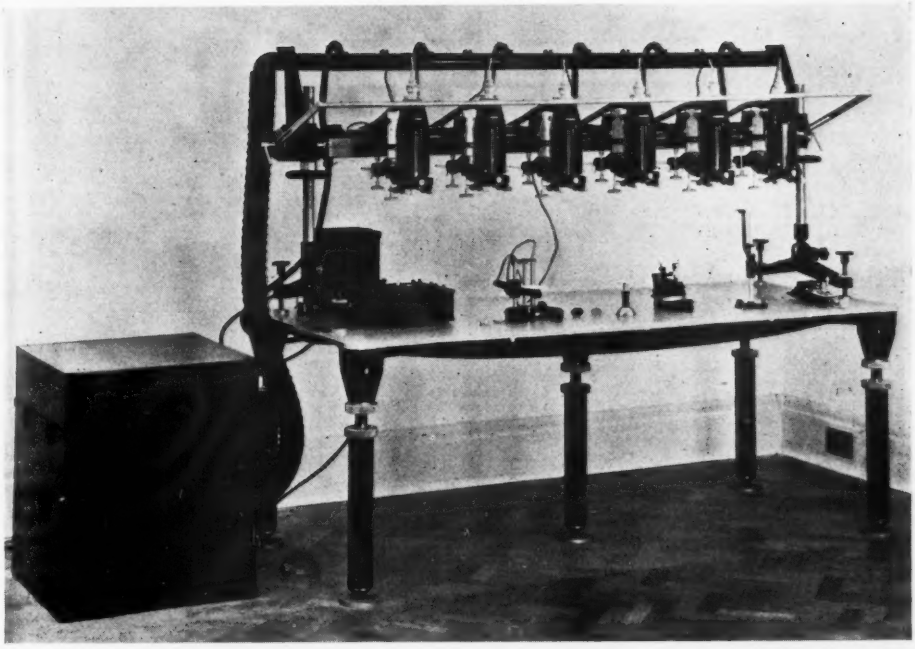


Fig. 11.
Williamson-Ross S.P.3 Multiplex equipment.

example of cost, the Netherlands Public Works Department, which carries out most of its contoured plans at a scale of 1/1,000 by photogrammetric methods, claims that comparing the overall expenditure of all ground survey, with combined air and ground survey, the latter method saves about 25 per cent. of the cost.

8. SOME RECENT EXAMPLES OF PHOTOGRAMMETRIC MAPPING

For topographical mapping no large scheme will ever again be undertaken without air photographs; the hey-day of the expert field plane-tabler is over, and most of his duties are now transferred to the office.

Photogrammetric advances are in the direction of improving photographic and mapping accuracy, while aiming at maximum economy and reduction of work on the ground. Many thousands of square miles have been mapped since the end of the 1939-45 War, from radar-controlled photographs taken by the R.A.F., by a combination of slotted template and multiplex. During the 1939-45 War, the "floating plane" method was evolved, whereby the ground control required for contouring was reduced by referring to a horizontal datum which could be inferred from the topography. This method has now been applied to multiplex mapping and developed with considerable success by the Colonial Survey Directorate. Topographical surveys of similar magnitude are in progress all over the world.

It is, however, for medium and large-scales that photogrammetry is now in process of establishing itself as a result of advances in techniques and improvements of accuracy.

In Great Britain air survey is looked upon as a method of surveying to be used when it is desirable, expedient and economical to do so. Without going into detail, it may be said that the use of air survey for both 1/1,250 and 1/2,500 scales has been accepted by the Ordnance Survey, although much of the work has still to be done on the ground. Contours are not required and the general approach is through the simple radial-line method with certain modifications. The Cambridge Stereocomparator (Fig. 13) is used for precise

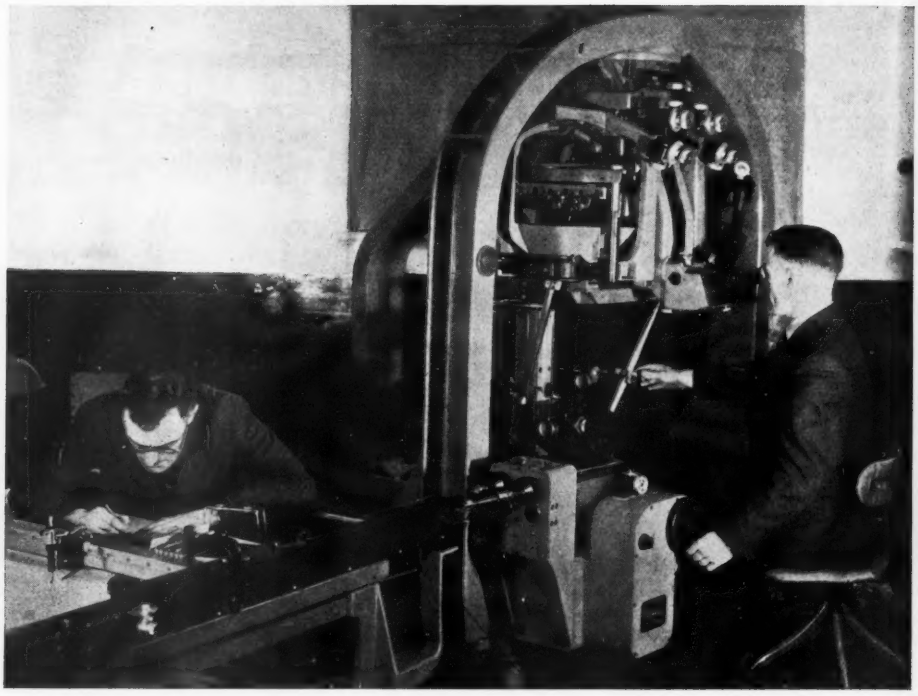


Fig. 12.
Swiss Wild A.5 Autograph as used by Hunting Aerosurveys Ltd.

stereoscopic measurement in breaking down the control. The chief difficulty has been the amount of computation required, but the results of recent researches at University College, London, indicate that this can be reduced.

Since Ordnance Survey large-scale plans do not show contours required for development, an important task of the two companies in the country concerned with air survey, namely the Air Survey Co. and Hunting Aerosurveys, has been to provide them where required for planning or engineering purposes. For commercial large-scale surveys, contours are almost invariably required and the companies do not employ radial triangulation, except where they are engaged on topographical mapping.

Photogrammetry has certain limitations for large scales, and it has, in the past, generally been accepted that 1/1,000 is about the limiting scale. At large scales, air survey must always be carried out in conjunction with some ground measurements, particularly on account of screening of detail.

Late in 1947, Hunting Aerosurveys undertook an experimental survey for the (then) Southern Railway* of Bournemouth Central Station, with track and marshalling yards at a scale of 40 feet to one inch (1/480). The photographs were taken with a plate camera, having a lens of negligible distortion controlled by carefully surveyed ground points, plotted by Wild A5 Autograph. The results of the experiment showed that overall planimetric accuracies of 9 inches could be obtained, and that the photogrammetric detail fitted efficiently into the "ground surveyed" positions, such as crossings which must be measured on the ground. Many lessons were learnt as to the relationship between ground survey and photogrammetry

* Dawe, H. G. Large-Scale Precision Mapping by Photogrammetric Methods. Photogrammetric Engineering (in the Press).

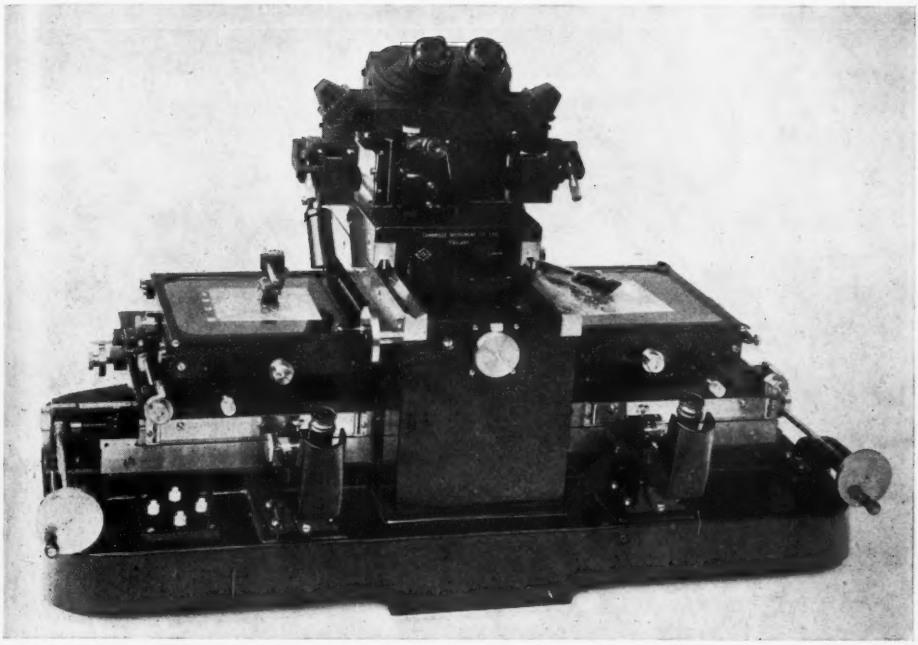


Fig. 13.
Cambridge stereo-comparator.

at these scales, and the experiment was considered successful, and economically worth while. Early in 1949, the Southern Region of British Railways called for a survey of the electrified railway from South Croydon to Purley Junction on the same scale. The work was carried out by co-operation between Hunting Aerosurveys and the railway surveyors and the results have shown that the 1/480 plan produced almost entirely by photogrammetric measurement provides a standard of accuracy acceptable for railway engineering.

Many surveys are now undertaken at large scales for public and commercial undertakings; for public works, mining companies, quarries and so on. As a final example, Fig. 14 shows a portion of a quarry survey, with corresponding photograph carried out by the Air Survey Co. with the aid of Multiplex equipment.

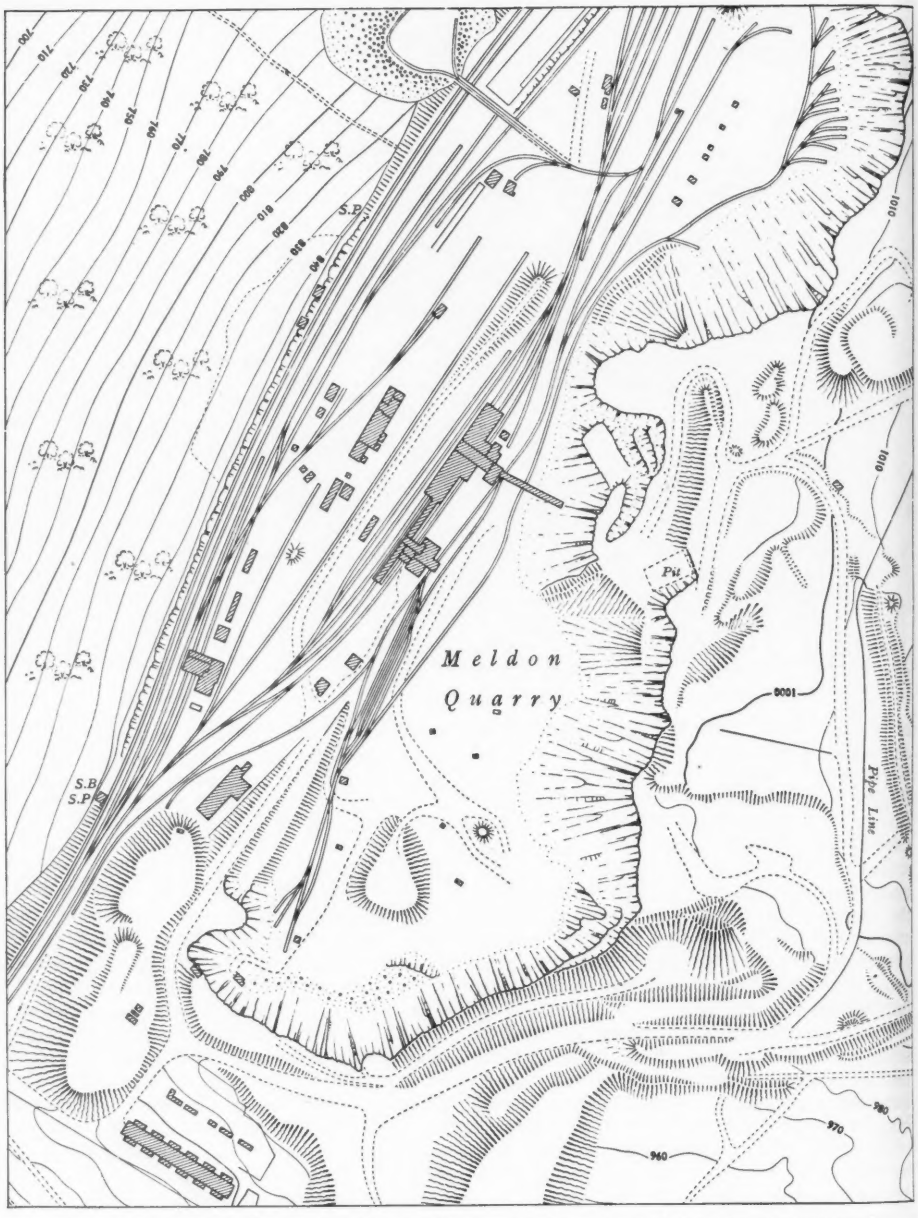
It is difficult to get at a precise statement of the proportion of detail to be surveyed on the ground and from air photographs. This depends upon the outlook of the surveyor and the specification to be fulfilled. The surest sign of the efficacy and economy of air photography for inspection and plotting at large scales is the increasing use to which it is being put by bodies which already have their own ground survey department.

9. MAPPING BY REMOTE CONTROL

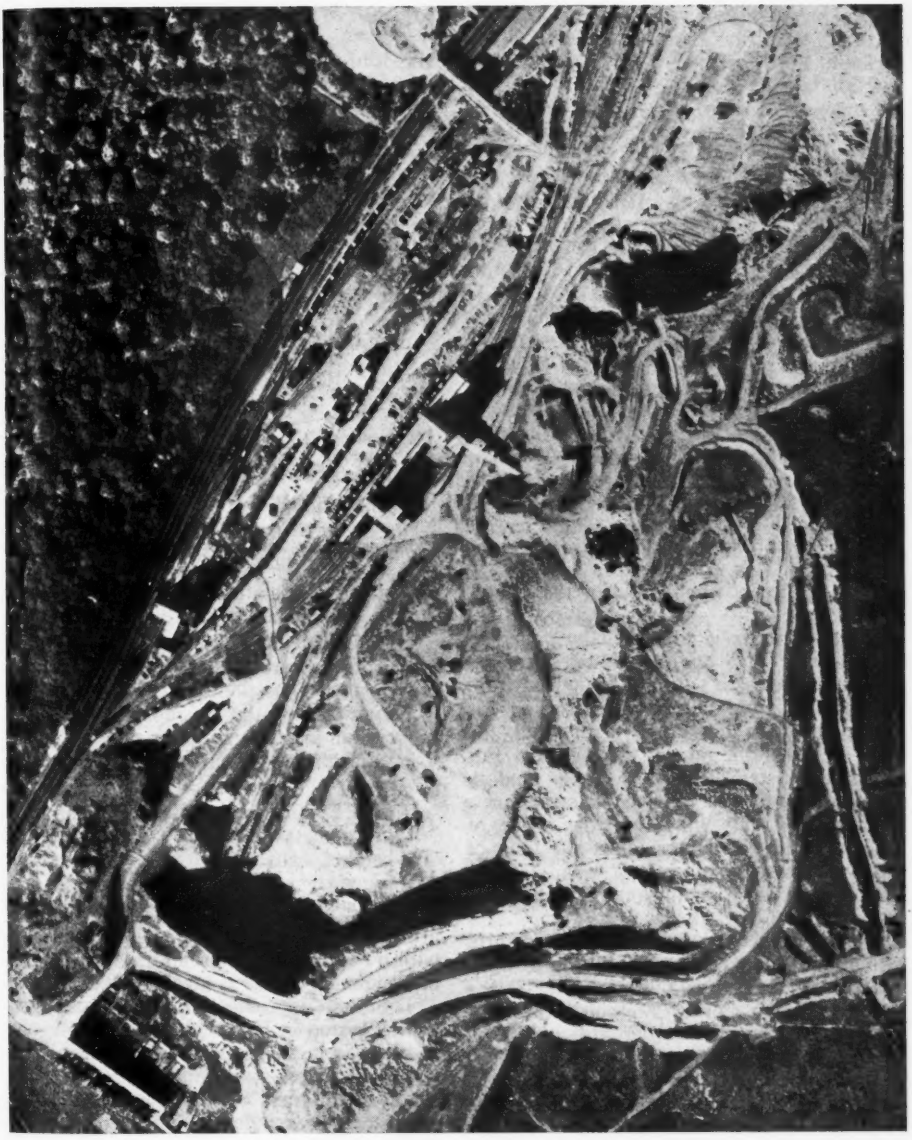
In addition to the control of navigation for strip photography by electronic methods, when the aircraft is fixed in space synchronously with exposure of the photograph, it is possible to use such fixes as control.

Although the hyperbolic method of fixation can be used in certain cases for this purpose, the circular fix has certain advantages. This particularly applies to the "angle of cut" of the rays being better conditioned over a wider area, and it is proposed here to describe briefly this aspect.

Surveying from air photographs has, until recently, been complicated by lack of direct knowledge of the position in space at the instant of photography. An elaborate pattern of ground-control points has been necessary to correct the photo-images for unknown



(*a*) Specimen of 1:2500 mapping of a granite quarry with contours at 10 feet vertical interval.



(*b*) Reduced mosaic of the same area.

Fig. 14.
Specimen of 1:2500 mapping of a granite quarry (opposite) with a reduced photographic mosaic of the same area by the Air Survey Co. Ltd.

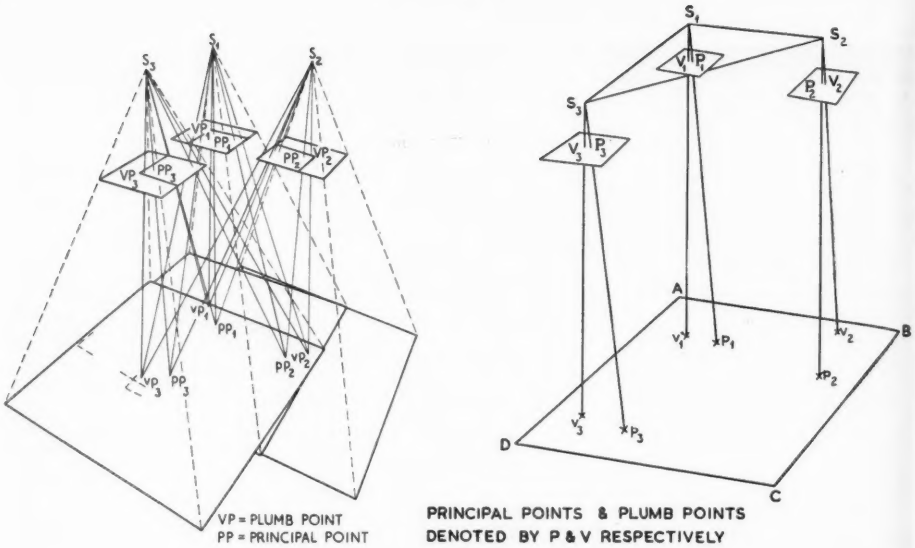


Fig. 15.

The "three corner" method. Lateral and forward overlaps between three air photographs.

location, scale and inclination of the photographs.

The aircraft fix is computed by spherical trigonometry and the positional error in relation to the earth's surface as defined from the remote ground controlled stations is dependent upon the range errors and the angle of cut of the rays at the aircraft. For a circular system (Fig. 5) with a random range error of ± 20 m., the fix error for a 30° angle of cut will be of the order of ± 60 m., and this factor limits the area of survey coverage from a pair of radar stations. This is even more significant for hyperbolic systems (Fig. 6*b*).

If photographs are flown by radar control with about 60 per cent. overlap both forward and laterally and lateral matching (Fig. 8), the pioneer "Three Corner Method" (Fig. 15) may be used to establish control points *on* the ground *from* the photographs. Four photographs contain a common overlap, a solution being found from that common to three photographs, the fourth being used as a check.

The process is in four stages:

(*i*) Measurement of the relative tilts between photographs 1 and 2, and 2 and 3 by precise photogrammetric methods;

(*ii*) By reference to the differences of altitude measured between exposures, the slope of the "air station plane" S_1, S_2, S_3 can be found and therefore the tilt of each photograph relative to the ground.

(*iii*) From accurate stereoscopic measurements on the photographs it is possible to calculate the position in space of certain control points in relation to the "air station plane."

(*iv*) From the slope of the "air station plane" to the horizontal the plan positions on the ground and relative heights of the control points can be found.

This provides sufficient data for preparing a map, with quite accurate relative contours, with no access to the ground other than that at the remote radar controlling stations.

The first experimental block was flown near Royston in Hertfordshire in 1944, some 85 miles from the ground stations, the aircraft being a Fortress, with automatic pilot giving steady conditions for altimetry. A Kollsman-type altimeter, reading to about 5 metres, was recorded at exposure, since a statoscope was not available. Four strips each of seven photographs were used for production of an experimental map. A six-inch lens was used, the photo-scale was about 17,000, and a 1/25,000 map covering some 65 sq. km. was produced. A 1/25,000 map was prepared and overprinted on the corresponding Ordnance

Survey map. The random error of plan position was about ±20 metres and of relative height about ±10 metres. Analysis of some 500 points of detail gave probable relative errors of ±8 metres and ±4 metres in plan and relative height respectively.

The man-hours required for such full investigation proved prohibitive, and subsequent work was devoted to simplification of procedure. Several methods were tried.

For plan, a simple and practical method giving comparable accuracy was to compute basic control at intervals of seven overlaps or so, giving five detail (or principal points) in each corner of a block. Slotted template assemblies based locally upon assemblies to groups of control points were improved by introduction of the "floating stud" by Trorey. This is a slotted template stud contained in a metal ring, and tensioned by three or four springs. A "floating stud" is used for each point of radar control and takes up a position of minimum strain in relation to the assembly, thereby automatically obtaining a mean fit and detecting gross errors. This method has been developed considerably by the Colonial Survey Directorate.

Relative tilts may be determined along the strip, and the absolute values deduced by summation along and transversely to the direction of flight on the assumption that there are constant corrections for particular flying conditions. This allows of reduction of lateral overlap from 60 per cent. required for the "Three Corner" method, to 20 per cent. and may well prove an effective means of employing radar fixes in conjunction with air triangulation. The employment of statoscope methods for measurement of relative altitude is considered essential if accuracy contours are required.

As a further example of a plan produced by "Gee-H" the Anglesey survey already quoted may be mentioned (Fig. 8). The "Three Corner" method was used in two diagonally opposite positions and a stereocomparator traverse run round the block. The complete plan control was produced in 39 man-hours, and after compilation of a one-inch map, the systematic error compared with the Ordnance Survey map was 50 metres while random errors were ±70 metres. Analysis of some 500 points of detail over the area of 800 sq. km., gave a probable error compared with the ground survey of ±25 metres.

Recently simplified applications have been put into effect, based upon the experimental results obtained during the 1939-45 War.

Altimetry still presents a major problem. Usually relative altimetry by statoscope methods can be achieved with reasonable accuracy, but that of absolute altimetry is still unsolved. It is impossible to discuss in any detail here, but the essence of the problem is that the surveyor requires altitudes above mean sea level, and for this he must so far rely upon barometric altimetry, which depends for measurement upon a standard atmosphere. Given complete knowledge of conditions of the atmospheric column between ground and aircraft, the necessary corrections can be made, but they are very complicated except for approximate results. Radar altimetry records the nearest point on the earth to the aircraft within the area of the beam, now narrowed to $1\frac{1}{2}°$ or so, and accuracies of direct measurements to 20 feet have been claimed. If the aircraft were a stable platform and did not vary in relation to mean sea level, along a strip, then the accuracy of ground profile determination would depend upon that of the altimeter. The Airborne Profile Recorder of the Photographic Survey Corporation of Canada has been developed to measure and record ground profiles for air survey. The method seems to have great possibilities for the future for pipe-line surveys and topographical mapping, and doubtless once the other unknown factors can be controlled, it will be possible to take full advantage of the accuracy claimed for the profile recorder. Nevertheless, it should at once prove of great value for reconnaissance.

10. THE NEW GEODESY

Radar range measurement of long lines involves flying an aircraft a number of times across the base between two radar stations. The minimum sum of ranges gives the point of transit, and reduction to the arc distance between stations can be made accurately, even if the aircraft altitude is not known precisely.

The method arose originally from a method employed for calibration in connection with the early experiments in radar survey carried out by the War Office from 1943.

For geodetic measurement we are limited to the ultra short-wave group of about one metre or less since the accuracy required is

of a very much higher order than for general navigation, or for some air survey purposes. The limit of accuracy for precise measurement is by no means reached.

Ranges measurable directly by radar are several times greater than anything possible by established optical methods. It has, therefore, been necessary to review the methods by which long lines on the spheroid have been computed in the past, since the accuracy of the standard must be established before that of radar ranging can be assessed. Distances measured experimentally by radar ranging are compared with the corresponding geodetic distance on the selected figure of the earth.

In addition to the elimination of errors of measurement of *time* and assessment of residual errors, accuracy of measurement of range by radar methods depends on a precise knowledge of the speed of propagation of the radio waves, and upon the path taken by them. The speed of propagation of electromagnetic waves in free space is theoretically independent of frequency and therefore equal to the speed of light.

Although the basic speed is known accurately enough for most navigational and air survey purposes, the greater accuracy of time measurement achievable by ultra-short wave systems necessitates more accurate knowledge of the fundamental speed.

In general, speed of propagation of short-wave radio waves in the air approximates that of light waves. For purposes of measurement of distance from time of transmission, the external influences on straight line transmission in free space must be assessed. These are principally:

(*a*) atmospheric conditions

(*b*) proximity of the ground

(*c*) diffraction: the property exhibited by electro-magnetic waves of bending round the earth.

Owing to the presence of the atmosphere, wave-length becomes a significant factor and, in general, accuracy of measurement and range of effective transmission are respectively inversely and directly proportional to it.

The assumption of average daily or seasonal rates of propagation, although satisfactory for most navigational and some survey requirements, is unsatisfactory when observations of high geodetic standard are undertaken.

In addition examination of local data shows that the deviation from linearity of the relationship between height and refraction may give rise to inaccuracies significant for geodetic purposes, so that knowledge of such local conditions is fundamental to the employment of radar measurement for geodetic purposes. Much research work remains to be carried out in this connection.

The first full-scale experiment was made in Italy in 1945, where measurements were made of a series of long lines undertaken by this method with previously calibrated apparatus. A base 618 km long measured from the mean of 22 flights at altitudes between 11,000 and 15,000 feet, gave an estimated accuracy, after investigation of propagation conditions, of between 1 in 20,000 and 30,000. Analysis of the range gave a probable error of ± 16 metres for a single reading and $\pm 3{\cdot}5$ metres for the arithmetic mean.

The original computation was based upon a speed of propagation derived from Michelson's value of the speed of light *in vacuo* using Englund, Crawford and Mumford's* formula. After applying corrections the measured base length was $618{,}320 \pm 3{\cdot}5$ metres while the computed length was 618,369 metres. Thus, although the arithmetic mean gave a probable error of only one part in 200,000 there was in addition a *systematic* error of one part in 15,000. By using the value of the speed of light determined by Essen†, the systematic error of 49 metres was reduced to about 5 metres.

An indication of the present accuracy obtainable has been derived by Jones and Cornford‡, § in their experiments on 9 cm Oboe.

Although Jones's experiments were primarily made for purposes of assessing speed it is possible to form an estimate of survey accuracy based upon the most reliable value of speed.

By using the Essen value for the speed of light which corresponds almost exactly with

* Englund, C., Crawford, A. B. and Mumford, W. W. Bell System. Tech Jour. Vol. 14, 1935. Vol. 17, 1938.

† Essen, L. Letter in "Nature," Vol. 195, No. 4044, 3 May 1947.

‡ Jones, F. E. Measurement of Velocity of Propagation of Centimetre Radio Waves. Jour. I.E.E., Vol. 94, Pt. III, No. 32, 1947.

§ Jones, F. E. and Cornford, E. G., Ibid. Jour. I.E.E., Vol. 96, Pt. III, September 1949.

that now considered by scientists in the U.S.A. to be the most reliable; by reduction of instrumental errors to the minimum, and accurate assessment of atmospheric conditions, it is possible to measure distances with an error of less than 5 metres.

For geodetic measurement the Shoran system has been most frequently used, and extensive experiments have been made. The first large-scale experiment was from Florida, by way of the Bahamas to S. America, and others have been made in the U.S.A., Australia and Canada. Many of the early difficulties have been overcome, and the method of flying across the base between radar stations has become well established.

The results of experiments carried out in Canada in 1948,* based upon a geodetic triangle, give an indication of the accuracy attainable at present:

Line	No. of flight crossings	Geodetic Length (miles)	Shoran Length (miles)	Discrepancy (ft.)	Accuracy to one part in
A	27	217.3787	217.3819	+17	68,000
B	17	273.0865	273.0832	−17	83,000
C	11	217.0887	217.0970	+44	26,000

It was concluded that probably about 16 line crossings are needed to give an accuracy considerably better than one in 30,000. This accuracy is expected to be doubled with improved equipment. The method has been accepted as accurate enough for providing control in Northern mapping operations, and it is stated that the positioning of stations by Shoran is definitely of very much superior accuracy to that obtained by astronomic fixation.

The work done so far shows clearly that the whole approach to geodetic surveys in the future must be modified, due to air survey methods. Here at last is the opportunity for world unification of triangulation nets. After further research it may well be possible to advance the study of the figure of the earth to an extent where a satisfactory world figure may be evolved.

It is necessary to point out that the indications so far are that the employment of radar will enable long connections to be made and assist in the assimilation and adjustment of frameworks, but there is no question of dispensing with present angular methods of normal triangulation work.

* Geodetic Survey of Canada. Shoran Experiments over the Geodetic Survey Framework in Ontario and Quebec. Bulletin Geodesique, 1949. Canadian Surveyor, Vol. IX, No. 12, April 1949.

11. CONCLUSIONS

It has been impossible in the space of one short paper to give more than an indication of the important part which air survey is playing in modern development. For instance, the use of airborne magnetometer surveys for prospecting. With the help of the airman, methods of surveying have now advanced far beyond the more or less static position occupied for many years; the modern surveyor and airman have grown up together and their team work has enabled such progress to be made that their joint contribution to economic development and its urgent needs is now fully recognised.

As an idea of perhaps the next phase, it is likely, too, that helicopters will be used extensively in the future for large-scale surveys. Air Survey is playing an ever increasing part in developed and undeveloped countries, alike, in order to fulfil the urgent economic needs of the modern world.

ACKNOWLEDGMENTS

The author acknowledges the assistance of all those who have helped in the preparation of the paper, in addition to those specifically acknowledged.

Acknowledgment is also made to the Royal Society, the Royal Geographical Society and the Institution of Civil Engineers, for permission to reproduce the following figures:—

Figures 5, 7, 15(*b*) from *Report of the Empire Scientific Conference*, Vol. I, 1948 (Royal Society).

Figure 1(*a*) from *Air Survey* Pamphlet; and

Figures 1(*a*), 2, 10, 15(*a*) from Hart, C. A.; Air Survey: The Modern Aspect. *Geographical Journal*, Vol. CVIII, Nos. 4-6, April 1947 (The Royal Geographical Society).

Figures 1(*b*), 6, 11 from Hart, C. A. Wartime Applications of Air Survey. *The Civil Engineer in War*, Vol. III (The Institution of Civil Engineers).

In addition to the references in the text the following papers by the author have been referred to in the preparation of this paper.

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2. Modern Mapping including the Employment of Radio Techniques. *Ibid.*
3. Air Survey: the Modern Aspect. *Geogr. Jour.* Vol. CVIII, Nos. 4-6. April 1947.

4. Recent Advances in Air Survey and their Application. Conference of British Commonwealth Survey Officers, London, 1947. *Jour. R.I.C.S.*, Vol. 27, Part V, November 1947.
5. Some War-time Applications of Air Survey. *Civil Engineer in War*, Vol. 3. I.C.E., 1948.
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8. The Influence of Modern Methods of Surveying on the Advancement of Public Works Engineering and Town Planning. Bossom Gift Lecture, Chadwick Trust. November 1949
9. Jointly with B. F. J. Bradbeer. Photographic Surveying in relation to Road Engineering in Highly Developed Countries. Road Paper No. 26. 9th March 1948. I.C.E.

DISCUSSION

E. A. Miskin (University College): Probably because the title of the paper was "Air Survey," the word "photogrammetry" had been used solely in its application to air survey. He was sure Professor Hart would agree that photogrammetry had a much wider field of application than air survey alone.

In 1944 radar was probably more accurate than it was in 1950, while the display had changed but little; there seemed to have been some retrogression in the use of that aid by the surveyor. On the other hand, there had been a corresponding increase in the use of radio navigational aids. It seemed that they had been rather backward in Great Britain, for whereas in 1944 and 1945 they were producing results for the Canadians and the Americans, in 1949 and 1950 the Canadians and Americans were producing the results.

The aircraft used for air survey by the Services nowadays were principally fighters of the Mosquito type, or bombers of the Lancaster type. The commercial firms were using aircraft which he considered to be more suitable for air surveying, types such as the Anson and suitably adapted modern twin-engined aircraft.

They had seen developments of cameras by the Swiss and the French, but there had been no reference to a modern plate camera which might have been developed in Great Britain.

Group Captain F. C. V. Laws (Air Survey Company): Much had been said about technical developments during and since the 1939-45 War, but little about the financial aspects of air survey which, from his point of view, was a vital factor.

He had had the privilege of being Chairman of a Committee appointed to investigate the application of radar to air survey. At that time Professor Hart was the Research Officer responsible for carrying out the recommendations of that Committee; this he had done as would be expected, with that detailed efficiency for which he had been noted in survey matters for many years. He had said quite rightly that radar control was likely to be beyond the scope of the air survey companies; that was only true insofar as those companies had not as yet been favoured with Government contracts of sufficient magnitude to enable them to invest in such equipment.

His Company was frequently faced with what might be described as a conglomerate of jobs so far apart that the employment of radar aids would be wholly uneconomical, nevertheless successes in operations had been, and were still being, achieved by other methods.

Professor Hart had referred to the necessity for the airman, surveyor and the photographer, in fact the complete team involved in the operation, to work closely together; that was really the most important factor in the commercial world of air survey. Technical improvements were of little avail without a sound organisation, a skilled staff and an adequate financial backing.

Since the beginning of air survey as a commercial enterprise, aircraft constructors in Great Britain had produced the backing which had enabled at least two companies to produce world-wide organisations operating throughout the British Empire. Those two companies were pioneers in the field and at the present time were producing maps of all scales and for many purposes, the subject matter for which would provide material for a paper of great importance.

The main feature in the specification for a modern aircraft camera could be summed up almost in one word, "reliability." The air survey pilot went out on sorties, frequently

from a base several hundreds of miles from his objective and it was vital that the camera, without any doubt, should function at the other end of that distance otherwise the whole of his work was wrecked and a great deal of money expended for no useful purpose.

During the 1939-45 War a specification was drawn up for the ideal mapping camera; this never matured and as the war ended something less elaborate had to be produced. He would like to see a camera made like a machine gun, substantially built, much heavier than the present instrument and something which could withstand hard wear and tear and could be serviced by an average mechanic in the field. Most surveys were made outside Great Britain, at least those that were economically worth while, so that those engaged on the work were always at a great distance from the instrument makers or manufacturers; that was why he stressed the need for reliability of the camera.

A question had been asked as to the best type of aircraft for air survey. At least four years ago that question was raised and he thought that the answer was still the same. There was no best type; practically every class of mapping work called for an aircraft of a different type. It was again a question of economics. If the job could be flown in an Anson it was a good aeroplane for the job, but looking to the future he felt that an aeroplane was required that could perform satisfactorily at about 35,000 ft. It must be capable of carrying its air crew, plus the photographers and ground staff, to distant objectives; on arrival at its destination it could disgorge its ground equipment and staff and then compete with its task. The possibility of transporting photographers, surveyors and their equipment by sea was out of the question. He believed that the Dakota, possibly with a Mamba engine, would provide in the near future the best solution for high altitude photography.

A. G. Sheppard (Deputy Chief Pilot, Hunting Aerosurveys Ltd.): Perhaps Professor Hart had been a little unfair in his comparison of the accuracies of the Decca Navigator and visual methods of navigation. One of the Companies which had been mentioned had carried out a survey for the Ordnance Survey in which the accuracy of navigation had to be kept down to a maximum of about 80 ft., and that was achieved quite successfully; however, he supposed that the Decca Navigator should be more accurate than that. He believed Professor Hart had stated that, because of the accuracy of navigation by Decca methods, the number of photographs employed was about half as many as were required when using visual aids. Was that always so?

Group Captain E. Fennessey (Decca Navigator Co. Ltd.): His interest in air survey was that of the electronic engineer, and it had been a particular pleasure to listen to Professor Hart, because about the year 1944, Colonel Hart, as he then was, had introduced him to some of the problems of air survey.

It had been said that the airman and the surveyor made a team. But Professor Hart seemed to have made clear that a third member of the team was the electronic engineer. The problems he had to face in meeting the requirements of the surveyor were great. It was true, as Group Captain Laws had said, that at present it was expensive to use radio or radar for survey; the small jobs could not stand the expense at the moment, but he felt that the large ones could. The ideal was that radar should meet the requirements of small blocks as well as large blocks. It must be apparent, however, that what the surveyor was asking the radar engineer to do was to measure time to within fractions of a millionth of a second in all parts of the world under all conditions of humidity, temperature, and so on. They could not do that at the moment except at some cost.

The radar station which was used during the 1939-45 War, when in fighting trim, had a staff of 50-60, of whom about a dozen were skilled radar engineers. The number had since been reduced. A Decca navigation station to-day could be worked by one man. Nevertheless, there was still great progress to be made in reducing costs. In the meantime, radar would probably be restricted to the larger operations.

Professor Hart had referred to propagation velocity; there were two principal radar or radio methods. One method used the very high frequencies (with Shoran something like 300 m/cs.), and the other method used very low frequencies, as in the case of Decca, of 100 k/cs. The low-frequency systems were stable from day to day. It had been suggested in the paper that there was a day-to-day variation. There was no day-to-day variation due to atmospheric conditions. But there was a variation with terrain; they could not be certain about the propagation of radio waves at 3,000 metres without

knowledge of the terrain over which they had passed. They might be dealing with an area in which the terrain was quite unknown in respect of geology. So that there might be poor results due to variation of velocity with terrain.

On the other hand, when using a method such as the Shoran, they had to contend with variation due to the temperature and humidity of the atmosphere through which the signals were passing, and that was unpredictable unless very accurate knowledge was received of conditions along the transmission path.

Whether the problem was attacked from the high-frequency or the low-frequency end, they came up against a minimum degree of accuracy on which, it seemed, they were not able to improve; it was round about 10 metres. There were claims in the United States to be able to carry out surveys by radar means to within an accuracy of inches. That was difficult to believe. There seemed to be a barrier at about 10 metres, and in his opinion they would not do better than that by means of any radio technique. They were up against variations of velocity for one reason or another which were unpredictable, and if they were to be more accurate they had to find other means than radio or radar.

The Decca navigation system had a new aid, in the form of a flight plotter. A drum carried a map, or a plain sheet of paper, on which the aircraft track was recorded as it flew. The flight strip could be laid out on the map for the survey operation, and the pilot could follow it; or alternatively he could use it as a reconnaissance aid by simply following the natural features, such as a river or coast line, and drawing it. That was now a reality, and it was a very useful tool for the surveyor.

P. G. Mott (Hunting Aerosurveys): In connection with large-scale surveys by photogrammetry Professor Hart had said that it was difficult to get a precise statement of the proportion of detail to be surveyed on the ground and from air photographs. There were two specific examples where such information was available.

The first was that of an original survey at 1/2400 scale of two square miles covering part of Durban Town, in South Africa. (1/2400 or 200 ft. to 1 in. to the mile.) The photogrammetric plans, which were also contoured at 10 ft. intervals, were later compared by the Survey Department of the City Engineer with reductions of a survey previously carried out on the ground at the scale of 1/500. The report on the comparison of the ground and aerial plots in that case showed that 95 per cent. of the detail had been correctly plotted from the air photographs.

The second and even more striking example referred to a recent experimental survey of a closely built-up section of Watford Town at a scale of 1/500 (42 ft. to 1 in.). The results of that survey had shown that 60 per cent. of the detail was plotted from the photographs with certainty and had proved to be correct when afterwards checked on the ground. Considering the very large scale of that plan and the fact that the area was specially selected on account of the density of the buildings, he felt that between 70 and 80 per cent. would be a fair average figure for the amount of detail plottable by photogrammetry in built-up areas at scales of 1/1250 and larger.

With such a considerable percentage of the survey already completed from air photographs, the remaining detail could be supplied rapidly on the ground by offset measurements. In fact, what took months to survey by ground methods alone could be supplied in weeks by a combination of air and ground work.

On the somewhat controversial question of the difference between visual and radar flying, he did not think the point had been made that most radar flying had to be necessarily on a pre-determined track. In many cases the air surveyor did not wish to follow a pre-determined track. He might be following the course of a route or communication such as a projected road, or a power transmission line, or he might be flying around the edge of a large lake, or he might for various reasons, particularly in mountainous countries, require to fly along the general alignment of the ridges and terrain. If he were flying on radar or Decca he had to go where the Decca line or the radar circle took him, whether he liked it or not.

The lecturer had stated that one of the great advantages of radar flying was the economy effected by reducing the lateral overlap. For certain mapping purposes it was essential when using a wide angle lens to increase rather than reduce the lateral overlap, owing to the excessive amount of distortion of this type of lens, which virtually meant that the outer one-inch of the photograph had to be eliminated. This particularly

applied in Multiplex bridging between control separated by long distances.

F. L. Wills (Managing Director, Hunting Aerosurveys Ltd.) *contributed*: There was a growing need for air survey and resultant mapping in the Commonwealth and Empire, and indeed over many parts of the world. The national resources of undeveloped countries had to be extracted to the utmost to keep civilisation going to catch up with the world shortage caused by the war and to supply future needs. Roads, transport, accommodation and plants had to be provided to move extracted minerals, timber and so on to the coast for distribution to overseas countries which were urgently in need. Air survey, including airborne magnetometer work, should be utilised in the early stages of this form of development and there should be an enormous demand for the necessary photography and mapping if a serious effort were made to "push ahead" with such schemes. That was where the flying, photography and mapping services of Civil survey companies ought to be employed, on speed and economic grounds, to augment the work of the Air Forces which were already heavily committed in other respects.

Mr. Miskin and Group Captain Laws had mentioned various types of aircraft. Percival Aircraft Ltd. had constructed for his company to their requirements the first post-war survey aircraft, known as the Survey Prince P.54 type. They took delivery in the early part of the year and the aircraft was now on its first survey operation in the Middle East. It was powered by two 250 h.p. Alvis Leonides engines, provided a range of 1,000 miles and a steady photographic ceiling at 24,000 feet. The aeroplane had a transparent nose, carried a crew of three—pilot, navigator/photographer and radio operator—as well as visual observers, such as geologists, if required. It was fitted with all arrangements of camera assemblies, including vertical, trimetrogon, split verticals, forward and side obliques and was considered to be one of the most economical twin-engined survey aircraft. It did not meet the visionary ideas of Group Captain Laws for high altitude flying at 30,000 feet and over, but those special requirements were only occasionally required.

N. E. Rowe (British European Airways, *Fellow*) *contributed*: A definition of requirements for survey aircraft did not come within the defined scope of the lecture, but it was important that a statement should be attempted. Group Captain Laws had somewhat lightheartedly suggested the DC-3 with Mamba engines, flying at 35,000 feet, presumably without pressure cabin and at a true speed of the order of 300 m.p.h.; he also wanted rather long ranges and the ability to transport men and photographic equipment to the area of survey. The author had referred to the probable extensive use of helicopters for large-scale surveys. Was that in addition to the fixed-wing machine, or in place of it, or as a complementary vehicle which could be used to ensure higher accuracy because of its special flying characteristics, especially the ability to hover?

He would like to see an objective statement of requirements, giving "payload," range and/or endurance, altitude, and forward speed of operation, economics, special requirements in relation to maintenance in the field, breakdown sizes, provision for installing equipment and services, stability and control. The latter might be of great importance for operation under automatic control, for circular flight, for accuracy of definition of the vertical. Jet propulsion with its avoidance of asymmetry associated with the normal propeller, might be of value for the last named, but the speed and heights of jet aircraft might be unsuitable. Airfield limitations, including size, height and ground temperature, were of fundamental importance in considering design and suitability of aircraft. This might sound rather a lot to ask for, but it would be of great value in enabling the air survey problem to be considered by designers in relation to other requirements, when laying down future designs.

The uses for the helicopter could perhaps be stated more generally, but range and weight of equipment to be carried and altitude of operation should be included.

PROFESSOR HART'S REPLY

Mr. Miskin: He had neglected the wider field of photogrammetry because he had not thought they would be interested in some of the strange medical practices, for example, to which photogrammetry was applied. It had a very wide application in all sorts of scientific and engineering ways. At University College, London, they were applying to all kinds of problems—problems of structural engineering and hydraulics; problems connected with metals, to accident survey (for example, in connection with road traffic or aircraft accidents, where a quick three-dimensional appreciation of a situation

was required)—and in many ways, quite apart from air survey. Photogrammetry was developing into a science, or perhaps it might be called a technique, of very wide application.

Probably no one was better qualified to deal with the question of suitable aircraft than Group Captain Laws who had had it on his mind for a good many years, particularly during the 1939-45 War.

The slowing down of radar development since the war had been a matter of considerable concern to many of those who had worked on it during that period; probably no one had felt more concern than had he and Mr. Miskin as they had worked together on the survey aspect from the beginning and always in close harmony with the R.A.F.

Mr. Sheppard: He had said that the comparison of the accuracies of the Decca Navigator and visual mehods was made between R.A.F. photography and Decca, for it must be remembered that photography was undertaken in the R.A.F. as part of the training, and the men flying could not expect to have the years of experience of survey flying that Mr. Sheppard and his colleagues had acquired, which enabled them to do very much better than was indicated by the figures quoted.

Group Captain Fennessey: He had had no intention of excluding the electronic engineer from the air survey team, where he took his place with the surveyor and the airman. Although he had mentioned the electronic engineer, he had not mentioned him especially; but he had been thinking of the difference between those who had worn brown and those who had worn blue during the war! Several specialists were needed in air survey; the airman took the photographs at the beginning, and finally the map printer put the results on to paper. There were also those dealing with the instruments, the meteorologist, and so on.

One particular matter which was disheartening was that, at the end of the 1939-45 War they had developed the art to the stage at which they could do something really worth while, and although it had been possible to continue survey work, albeit in rather more primitive style than they would have wished, they had hoped there would have been a priority or an incentive to develop radar aids to cut down the number of people required to operate stations and to reduce the cost of general construction of stations. No one had worked on that problem more continuously or more effectively than had Group Captain Fennessey, because during the war he was actively concerned with radar survey, and he was now concerned with the Decca Navigator, which under his guidance had become a valuable survey instrument.

The Gee-H experimental stations were run for about a year by two scientists and two airmen. But once the stations were established as R.A.F. units there were in each case two officers and 29 men—Adjutant, cooks, and so on! In peacetime that could not be afforded. Consequently, they had fallen down because they needed proper priorities in order to develop those aids so that the expense of running the stations could be reduced. From war experience the Decca Navigator had succeeded very largely in doing that.

It was interesting to hear that recent experiments had shown the Decca propagation through the atmosphere to be stable. Perhaps they were talking rather at cross purposes in that connection. For survey work for topographical purposes, where a mean rate of propagation could be taken, those anomalies were not so important; but if they were concerned with the measurement of long lines for geodetic purposes, small variations day to day, due to atmospheric changes, were extremely important both for short and long wave lengths, the effect for the long waves being notably greater. He did not think therefore that there was any real disagreement between them in the matter.

He agreed that 10 metres was about the present limit of accuracy for a single observation. He had quoted the figure of five metres because this had been achieved consistently in a series of repeated readings along a fixed bare line. With the aid of the helicopter they might be able to obtain repeated readings, probably 50 within a short time, to get a more accurate fix. That was a line along which advance might be made.

Mr. Mott: The amount of ground work required for large-scale survey was a subject for further discussion, because it depended largely on the specification, and on the type of ground. If a representative of the Ordnance Survey were present, probably he would tell a very different story. Perhaps one person was more conservative than another; perhaps the percentage actually to be obtained on a strictly comparable basis

lay somewhere in between; but there was no doubt that a considerable amount of information could be obtained from the air photograph, although in fairly heavily wooded and screened areas much detail was obscured. There was no doubt that the proportion of measurements to be obtained from air survey was remarkable.

Experiments had been in progress on straight line navigation in any selected direction by the use of radar. However, it was quite clear that a really experienced survey pilot could produce remarkable results in covering an area, provided that he had a good or reasonable map on which to base his flying programme.

When he had mentioned lateral overlap he was thinking more particularly of maps of large topographical scale, because the radar type of navigation was not really suitable for large scale, except, of course, the Decca Navigator where, and when flying at large scales, a wide angle lens would not normally be used—so that he did not think there was any disagreement between them. It meant that, for topographical mapping, the overlap could be cut but when it was important to confine the work to the centre of an area, where great accuracy was required, the overlap would be increased.

Mr. Rowe: The helicopter would not fulfil the r[illegible]ements laid down by Group Capta[illegible] for high altitudes and long rang[illegible] appeared to be in two main capac[illegible]

(*a*) That already mentioned, wherein by repetition of comparatively short range radar measurements from an airborne stabilised platform, an approach could be made to the surveyor's ideal requirements in space of known altitude, position and inclination. That would reduce the ground work considerably. Even without the aid of radar it would probably prove very advantageous.

(*b*) For ground control and reconnaissance. For example, in Canada it was being used for this purpose for topographical surveys, as well as for low altitude photography and ground control areas to provide surer indentification of the points on smaller scale photographs.

He was not competent to discuss aircraft types. He was concerned with getting air photographs taken under strictly scientific conditions for his particular purpose. The results he obtained were dependent upon the airman, and were often conditioned by the different specifications for service and civil aircraft.

REDUX BONDING OF AIRCRAFT STRUCTURES

by

C. J. MOSS, B.Sc.

INTRODUCTION

That synthetic glues for wood were used extensively for making Mosquito and Hornet aircraft during the 1939-45 War, and are now used for making Vampires in many European countries, is well known to aeronautical engineers, but not so well known is the fact that, since 1944, synthetic glues for metals have been used in the production of many hundreds of military and civil aircraft. A glue for metals, which gives joints stronger than can be obtained by riveting and which is also resistant to the severe conditions to which aircraft are exposed in service, offers the possibilities of savings in structure weight and of aerodynamically cleaner wing and fuselage surfaces. Such a glue may also be expected to be of value in the manufacture of pressurised fuselages, because it will avoid the large number of small leaks occurring at the rivet heads and may also help to solve the difficult problem of making integral fuel tanks in aircraft wings.

Any savings in structure weight or drag which may be possible on a high performance jet-propelled aeroplane must be of even greater importance than on a piston-engined aircraft, because of the relatively high fuel consumption of gas turbines. It is interesting therefore to learn that the "Redux" process of metal bonding has been used extensively by de Havilland Aircraft Co. Ltd. in the construction of the wings and fuselage of the Comet. As this Company has already had many years' experience of using Redux on a number of smaller aircraft, it may be concluded that the results obtained must have been very encouraging for them to use the process in an even more ambitious way on their latest and most advanced aircraft.

The earliest use of Redux in aircraft construction was in the manufacture of the Hornet single-seat fighter. The de Havilland Aircraft Co. Ltd. was faced with a difficult problem because of the large wooden booms required for the wing spars. The difficulty was overcome by making the tension booms of aluminium alloy extrusions but still using wood for the spar webs and compression booms. The metal and wood were then glued together so as to form a spar of remarkably low weight and high strength. Many Hornets have been operating with the Royal Air Force and the Royal Navy and have given excellent service.

A somewhat similar design is used by Vickers-Armstrongs Limited for the floors of the Viking and Viscount. Aluminium alloy top-hat stringers are bonded to the undersides of sheets of plywood to form floors whose upper surfaces are quite free from any rivet or bolt heads. Vikings of the British European Airways Corporation have now flown for considerable numbers of hours and no trouble has been reported with the Redux. A more recent example of metal-to-wood bonding may be found in the fin of the Canberra jet-propelled bomber. The fin is of wooden construction because it houses some aerials and it is attached to the extruded aluminium alloy spars by means of the Redux process.

Although these uses of the process for bonding metal to wood are of interest, the application of Redux to all-metal structures is likely to prove of far greater importance, for it seems likely that high performance aircraft of the future will be of all-metal construction. The need for smooth thin wings is more pressing than ever and the hitherto normal riveted construction is open to criticism, both because of the need to keep structure weights to a minimum and because of the aerodynamic effect of the rivet heads. Most aircraft skins are covered with rivet heads and consequently, determined efforts

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Lecture given to the Graduates' and Students' Section of the Royal Aeronautical Society on 8th December 1949.

Mr. Moss is Project Engineer, Aero-Research Ltd.

have been made to diminish their effect either by machining their heads or by finishing the wing surface with special fillers. Spot welding has been used but even this leaves small marks where the electrode makes contact with the skin.

A gluing process offers an entirely different line of approach in the making of all-metal aircraft structures. It was used successfully on the Dove and is now employed on the Comet; in the next few years it will be used on a number of other aircraft, but most of them may not be discussed yet.

It is interesting to note that Redux has already been used by The Bristol Aeroplane Co. Ltd., in the construction of their single-rotor and twin-rotor helicopters. The process has provided a convenient way of attaching metal trim tabs to wooden rotor blades and has been of great value in making experimental metal rotor blades. It has also been used in the construction of the fuselages of both types.

STRENGTH OF GLUED JOINTS

Glued joints should be designed, as far as possible, for loading in shear but, unfortunately, it is not possible to describe in a simple way how the failing load varies with changes in dimensions of the joint. As might be expected, the breaking load does vary in proportion to the width of the joint but it is only proportional to the joint length for very small overlaps. For larger ones it scarcely increases with length of overlap. The strength of the joint also increases (1) with the thickness and (2) with the mechanical properties of the metal test pieces.

The explanation of this behaviour is to be found in the stress concentrations in the joints. The load is not uniformly distributed over the whole of the glued area but is mostly taken by the ends of the joints. The stress concentrations may be considerably reduced by tapering the metal test pieces, with a corresponding increase in failing load of the joint, but it seems unlikely that tapering the metal would be an attractive proposition in practice.

Another aspect of this matter is the way in which the strength of the joint varies approximately in proportion to the yield point* of the metal strips used to make the joints. Table I, giving failing loads of ½ in. overlap joints made from 20 s.w.g. strips of metal, illustrates this point.

TABLE I

Material	*Failing load of Redux joint (lb/sq. in.)*	*Yield point of metal strip (tons/sq. in.)*
Aluminium—half-hard	1,100	5.8
"Alclad" —DTD 390	3,600	15
DTD 546	4,000	21
DTD 687	5,000	26

The failing loads given in this Table for glued joints between strips of "Alclad" are several times higher than can be obtained with spot welding or riveting. Care must be exercised however in applying the results of these small scale tests to the design of aircraft structures, and I believe that the following results are likely to prove of far greater interest to designers. This is particularly true because in many of them there is a direct comparison between the strengths of riveted and glued panels when tested in the way that they are loaded in an aircraft structure. The Gloster Aircraft Company Limited tested some panels of a design somewhat similar to those used on the Meteor. They consisted of a 24 s.w.g. skin to which a 24 s.w.g. top-hat stringer was bonded. In compression this panel failed at an average load of 2.5 tons, while a similar riveted panel only withstood an average load of 1.8 tons. Thus the Redux-bonded panel carried an average load 40 per cent. greater than that of the riveted panel. The corresponding figures for test specimens consisting of a 24 s.w.g. skin with two 24 s.w.g. stringers were 4.25 tons for Redux, and 3.16 tons for riveting.

A further point must be borne in mind when considering these results. The panels were designed for riveting and not for Redux bonding. It is possible that had the stringers been modified (but without increasing their weight), still higher results with Redux might have been obtained. Redux bonding is an entirely new technique and the best results are only obtained if the design is made for gluing. A design which is suitable for riveting is not necessarily suitable for gluing, and *vice versa.*

Another interesting series of tests has been carried out by the Bristol Aeroplane

*0.1 per cent. proof stress.

Company. In these experiments a panel reinforced by stiffeners was bolted round its edges to a box and submitted to a fluctuating air pressure similar to that occurring, for example, on the trailing edge of an aircraft wing. The panels were all 40 in. × 24 in. and the $\frac{1}{2}$ in. × $\frac{1}{2}$ in. × 20 s.w.g. stiffening angles were all parallel to the shorter edge. The first panels had 22 s.w.g. skins and were of a riveted construction. One failed after 0.3×10^6 cycles of stress and the second, of a slightly modified design, after 0.7×10^6 cycles, and the failures were of a similar kind to those which had occurred in flight, *i.e.* by skin cracks beginning at rivet holes.

When a similar panel in which the stringers were Redux-bonded to the 22 s.w.g. skin was tested, failure did not occur until after 4.5×10^6 cycles of stress, and only then because the metal stringer cracked. The Redux bond appeared to be in perfect condition after more than six times as many stress reversals as were required to cause skin cracking at the stress concentration of the riveted panel.

Three further tests were carried out using the same cycle of air pressures in the box but with 24, 26 and 30 s.w.g. skins. For the two thinner panels the stiffeners were spaced at 4 in. intervals, but for the two heavier ones the spacing was 8 in. The following results were obtained:—

24 s.w.g. panel failed after 2.1×10^6 cycles by cracking of the metal stringer. Redux bond still intact.

26 s.w.g. panel failed after 2.4×10^6 cycles. Redux bond failed.

30 s.w.g. panel failed after 5×10^6 cycles by cracking of the metal stringer. Redux bond still intact.

The de Havilland Aircraft Co. Ltd. have also carried out many tests and we know that their designers reached similar conclusions, *i.e.* that Redux-bonded panels will carry far higher loads than riveted panels. In addition to tests at room temperature, they have carried out compression tests on panels at high and low temperatures as well as fatigue investigations. Perhaps the most interesting test that has ever been done on a Redux-bonded structure was made on the complete wing of a Dove aircraft. This wing was subjected to the following series of repeated loadings:—

1,200 cycles from 0 to 2 *g*.
500 cycles from 0 to 2.45 *g*.
5 cycles from 0 to 3.4 *g*.
10,000 cycles from 0 to 1.5 *g*.
5 cycles from 0 to 3.86 *g*.
5 cycles from 0 to 4.37 *g*.

After nearly 12,00 cycles of stress the wing was in perfect condition and it was decided to subject it to static loading until failure occurred. This was at 5.5 *g*. which was about 8 per cent. above the design load.

The photographs accompanying this paper give some explanation of why such good results were obtained. The appearance of the wing under load is quite different from that of one of riveted construction. In the latter, the buckles all run through the areas of stress concentration, *i.e.* the rivet holes. With a bonded wing it will be seen that the skin is held firmly along the whole length and the whole width of the stringers. Such a construction is stronger than one in which the skin is drilled with numerous holes for rivets and in which the load is transferred at these holes. With the stringers glued to the skin the buckles are localised between the stringers and are unable to run right across the wing.

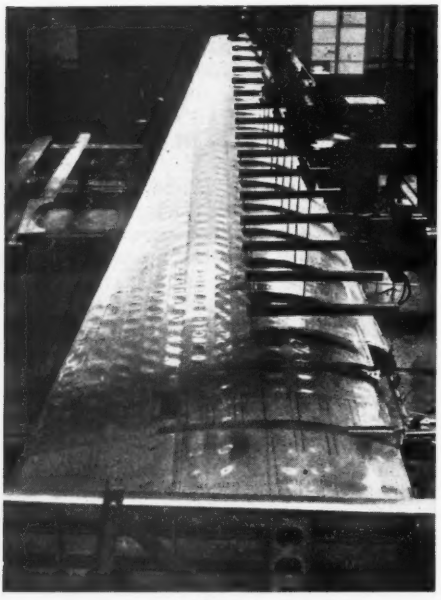

Figure 1.

A severe repeated loading test was carried out on the complete wing of a Dove. This photograph of the wing under load shows that the skin buckles are localised between stringers and do not run continuously across the wing.

When the Dove wing was examined after the completion of the test it was revealed that even where the metal skin had fractured, only one stringer had parted from it for a short length. Had a conventional riveted structure been subjected to a similar test, it is probable that either the rivet heads would have come off or pulled through the 22 s.w.g. skin.

If confirmation of this test is required it may be found in the experience which has gradually accumulated with the 300 Dove aircraft now in service. One of them in Australia has flown no less than 3,400 hours in two years, an average of more than 4 hours flying daily. Others have operated satisfactorily in tropical Africa.

After examining the results of these strength tests of various kinds on Redux-bonded structures, it is interesting to consider an example of how the weight of a structure may sometimes be reduced by changing from a riveted to a bonded design. The Bristol Aeroplane Company have made some servo control tabs from 30 s.w.g. material, *i.e.* from sheet which is only 0.0124 in. thick, and which it would be almost impossible to rivet. These tabs are particularly interesting because there is not only the direct weight reduction on the tabs themselves but also the weight saving on their balances. The total reduction is likely to be about 200 lb. on the weight of tabs and balances for a typical four-engined air liner. Perhaps this figure will be more vividly appreciated if it is realised that it is roughly equal to the weight of one passenger and luggage.

Having considered some of the advantages which may result from the use of Redux, it is necessary to mention briefly the actual technique of bonding aircraft structures. Although naturally a glue is desired which will bond metals together at room temperature, it has unfortunately not yet proved possible to develop a cold-setting adhesive that has sufficient strength, together with adequate resistance to tropical temperatures and humidities, and to common solvents (petrol, lubricating oil, and so on). It is a disadvantage that the Redux process requires

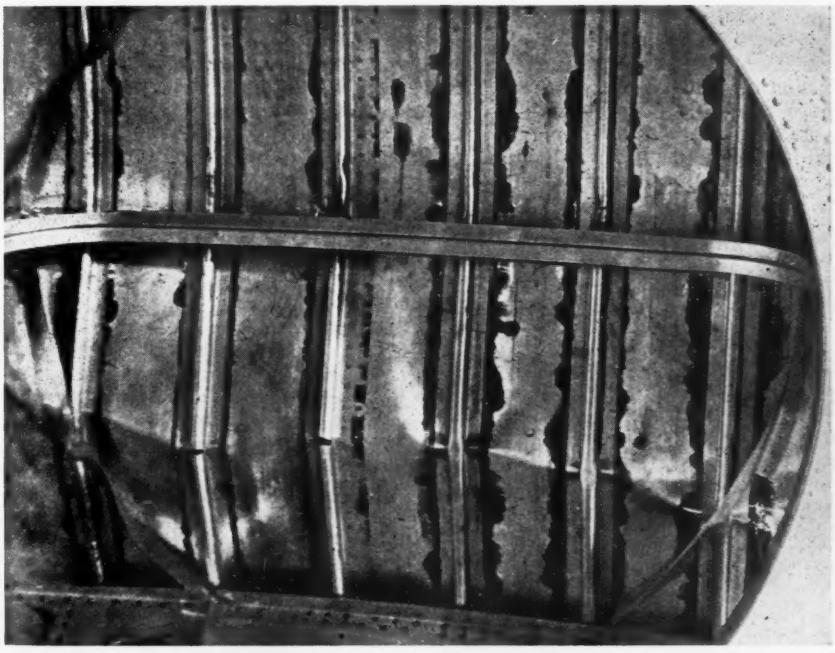

Figure 2.

Failure of the Dove wing eventually occurred at 8 per cent. above the design load. Although two of the metal stringers failed the Redux bond remained intact, except for small areas on either side of the fractured metal.

Figure 3
A servo tab made from 30 s.w.g (0.0124 in. thick) aluminium alloy sheet. It would have been impossible to rivet satisfactorily such thin sheet.

a combination of heat and pressure for "curing," but the temperature is only 140-150°C., which is not sufficient to have any material effect on the mechanical properties of aluminium alloys, and which is not sufficient to render them liable to intercrystalline corrosion. Pressures of 100-200 lb./sq. in. are all that is necessary, and in fact much lower ones have been used on an experimental scale and have given perfectly satisfactory results.

Most of the early production of Redux-bonded components has been carried out using steam-heated hydraulic presses. At Aero Research Limited, Duxford, by whom the bonding process was developed, such a press has been used for many years to carry out bonding for aircraft constructors as well as for many other engineering firms. In their production of fuselage and wing panels for the Dove, the de Havilland Aircraft Co. Ltd. have used a similar but larger press. Their normal production method is to bond in one operation numerous stringers to skins about 12 ft. long by 4 ft. wide. The panels made in this way are then wrapped round and riveted to the wing ribs or fuselage frames. It is worth considering the amount of work required to jig drill each rivet hole in the stringers and then in the skin, and afterwards to countersink each hole in the skin before actually doing the riveting, and to contrast this with the fact that after degreasing and chemical cleaning of the metal parts, they are all bonded together in one operation, requiring perhaps a total time of about half an hour.

A French aircraft constructor has used an electrically-heated press to bond thin wood veneers to extruded aluminium alloy wing spars. The temperature of the spar in the press is checked by a number of thermocouples in small holes in relatively unstressed parts of the spar itself, and the pressure required for bonding is applied by means of a number of hydraulic rams along the length of the press. The same firm has also bonded wood veneers to light alloy wing ribs by

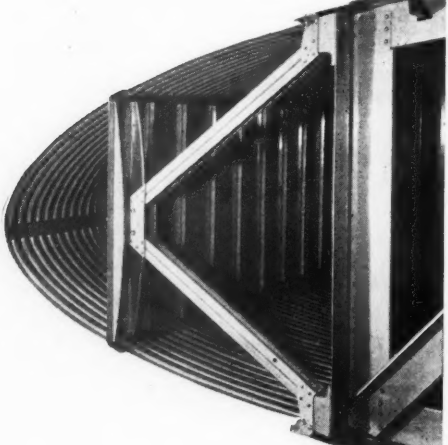

Figure 4.

The Bristol Aeroplane Co. have developed a wing leading edge design which is particularly suitable for bonding. A corrugated inner skin is bonded in an autoclave to a plain curved skin to provide a panel of remarkable stiffness and strength.

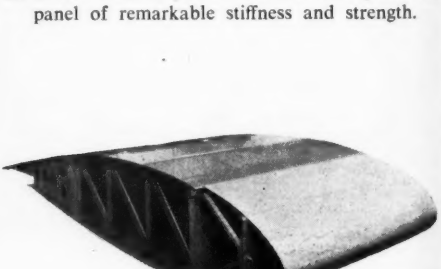

Figure 5.

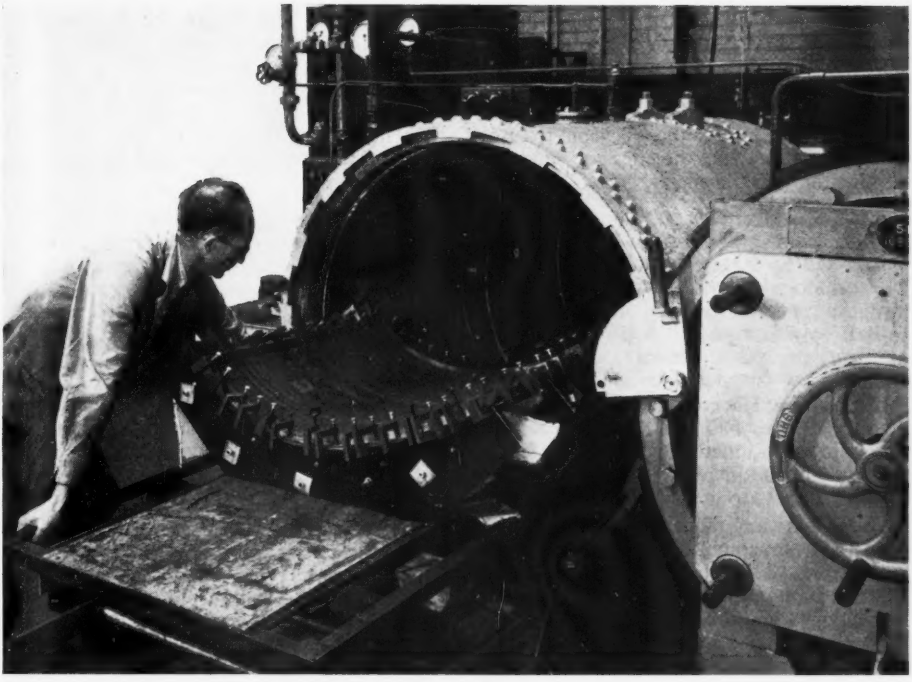

Figure 6.

The use of an autoclave for Redux bonding has been found by the Bristol Aeroplane Co. to give excellent results. The panels (illustrated in Fig. 5) are placed on a suitable jig, covered by a rubber blanket and put in the autoclave. Air is pumped in to apply the pressure required for bonding and heat is then supplied by electric resistance heaters under the jig.

clamping the parts together and curing the resin in an oven.

Although steam and electrically-heated presses will no doubt continue to be used extensively for Redux bonding, there are limits to the type of work for which they can be used. They are probably the most economical plant for bonding flat components or for those which are thin enough to be formed to shape after bonding, but they are not at all suitable for dealing with doubly curved panels. To overcome this difficulty the Bristol Aeroplane Co. Ltd. have adapted an autoclave to bond the leading edges of one of their new aircraft. The degreased and chemically cleaned metal parts are treated with Redux liquid and powder, placed on a curved jig, covered with a rubber blanket, and then put in the autoclave. Air is pumped into the autoclave to provide the necessary bonding pressure and then heat is supplied by an array of electrically-heated mats under the curved jigs. Considerable ingenuity has been shown in this development with the result that the Bristol Aeroplane Co. Ltd. have a technique which can be applied to an almost unlimited variety of doubly curved panels. It is also an interesting fact that the Redux joints made in an autoclave appear to be of a better quality than those made in a press.

CONCLUSION

It is hoped that this paper has succeeded in showing the advantages which may be obtained from the proper use of glues for metals. At the same time it will be recognised that the change from riveted constructions to bonded assemblies requires something more than taking out the rivets and putting a glue in their place. For example, if extruded stringers with flat bases are bonded to an accurately curved skin, then some distortion must be expected in the finished assembly. It is evident that a flat

surface cannot be glued over the whole of its area to a curved surface without some distortion occurring, whereas such a design may be suitable for riveting.

If full advantage of the gluing process is to be obtained then the decision to use it must be taken at the design stage and production arrangements must be made accordingly. The use of the process often requires the introduction of completely new designs, or the modification of existing designs and it certainly requires a big change in production methods. Sufficient experience has now been obtained to show that such changes are frequently justified by the results obtained.

DISCUSSION

F. Neilson Hancock (A.I.D., Ministry of Supply, *Assoc. Fellow*), *contributed*: What were the signs, methods and other features involved in the inspection of a Redux joint, compared, say, to an old Casein-glued joint?

Were there any modern methods of inspection (*e.g.* ultrasonic, fluorescent, inductance, etc.) which could be effectively applied to Redux joints, although they were unsuitable for older gluing processes?

With the older methods of gluing, it was found that tacking or screwing together the parts to be joined, increased the reliability and consistency of the joint. Was there any parallel for Redux joints (*e.g.* by the use of spot welding or other local attachments)?

What was the degree of electrical conductivity of Redux-jointed metal parts? In other words, how was 'electrical bonding' of Redux components affected and effected:

How were Redux joints affected by very low temperatures alternating over long periods, such as would be experienced in wing skins on trans-Atlantic flights?

D. James (Vickers - Armstrongs Ltd., *Assoc. Fellow*), *contributed*: The figures quoted by Mr. Moss on the failing loads of panels appeared very convincing, but it might be asked whether, even though the panels were designed for riveting, some slight alteration in the detail design, such as a close rivet pitch, would not have produced a strength comparable with that of the Redux panels. The results given were for panels of very light construction. He had seen panels of fairly heavy construction tested in which the Redux panels showed no increase of strength over the riveted panels and in those cases the failure of the Redux bond extended practically the full length of the stringer. It was not suggested that that was the primary cause of failure. The question of an increase in strength due to the use of Redux instead of riveting was probably determined by the mode of failure to be expected. In very light structures in which "inter-rivet buckling" played a part, Redux would probably show to advantage.

The smooth finish produced by Redux was not as straightforward as might appear at first sight. When the manufacturer supplied a flat sheet it had been stretched to take out all the slack patches in the sheet. The Redux process involved raising the temperature of the sheet to about 140°C., a process which undid all the good work done by the manufacturer in his stretching operation and might well result in a very strong joint between two very wavy sheets of metal. This would not produce a contour to please the aerodynamicist.

H. Giddings (Bristol Aeroplane Co. Ltd., *Assoc. Fellow*), *contributed*: The paper was a useful general discourse on the present state of development, scope and advantages of Redux bonding. He could enlarge on the advantages and give additional applications to those quoted but it would be dangerous to generalise too much from the particular examples quoted and to assume that they only had to "Redux" to obtain a stronger, lighter or smoother structure. He agreed entirely with Mr. James' particular comments. Riveted compression panels, properly designed, could be as strong as Redux panels in some cases. In some panels they had tested, panel distortion during the Redux process had actually produced failures at loads below those of similar panels of riveted construction.

Distortion during the curing of the Redux was a serious problem, both from the point of view of surface finish and also of structural strength. In a stiffened skin compression panel the distortions could take the form of local buckles between stringers, and also, more seriously, of lateral bow along the length of the stringers.

He did not think that the reasons for this distortion were yet clearly understood and was not sure that Mr. James' explanation was the correct one, although it was possible.

The performance of the Redux bond at elevated temperatures gave some cause for concern. At 90°C. the reduction in strength was some 50 per cent. of that at normal temperature, falling off very rapidly above that. Skin temperatures of that magnitude would be expected at low altitudes in the tropics but apparently the de Havilland Company's operating experience under those conditions had so far been satisfactory.

No aircraft production organisation should enter the Redux bonding field lightly. The key to success was close process control, particularly over cleanliness, and those things were not found in many existing aircraft production shops. To most, a new outlook would be required.

The inspection techniques for Redux were also not too well established. The present form of "Peeling" test left much to be desired and some form of non-destructive scanning test was urgently needed.

Data on production costs would also be appreciated by those contemplating use of the process. He was sure that Mr. Moss could now give useful information on that, from the accumulated experience of his Company.

The fundamental advantages were there, and it was only by more general use that those problems would be solved.

F. Tyson (Handley-Page Ltd., *Assoc. Fellow*), *contributed*: The advantage of Redux joints in producing a better external finish, and allowing some saving of structure weight, were now sufficiently well established to ensure that the use of Redux would increase in the next few years.

Three points mentioned by Mr. Moss were worth emphasising. First, it was not enough merely to substitute Redux for rivets in a conventionally designed component. The full advantages of Redux could only be realised if the structure were designed to suit Redux bonding. How this should be done could not be explained in a few words. The factors influencing the changed design requirements were the different nature and behaviour of Redux and riveted joints, and the way in which a Redux-bonded component was made in the workshops. Second, the new technique of Redux bonding in an autoclave was an important advance. It gave a more uniform pressure on the Redux film during curing than could be obtained in a press, and so allowed a lower bonding pressure to be used. It also allowed Redux bonding to be extended to a larger range of applications (*e.g.* components with curved formers, or double curvature skins) than could be made in a press. Third, a well-designed Redux-bonded component should be superior in fatigue strength to a riveted component of the same static strength, because the stress concentrations at the rivets were avoided.

An aspect of Redux bonding which Mr. Moss had not emphasised was that making good Redux joints in aircraft structures was not a simple matter. Development work was required in the workshops before jobs of satisfactory strength, and free from objectionable distortions, could be produced consistently. When this stage had been reached, a high standard of cleanliness, and a strict control of processes (including taking regular samples for testing), must be maintained to ensure a satisfactory standard of production.

It would be interesting to know how Mr. Moss arrived at his startling figure of 200 lb. for the weight saving due to changing from riveted to Redux-bonded tabs on a typical four-engined air liner. It was considerably less, according to his calculations, as the following figures showed:—

Total weight of tabs (spring tabs, balance tabs and trimming tabs) including tab mass balances, say 40 lb. Weight saving on this due to Redux bonding, say 25 per cent.—10 lb. Further saving on main control surfaces mass balance due to reduction in tab weight, 30 lb. Total weight saving, 40 lb.

If the weight of tabs were much more than 40 lb. an aircraft, or if the weight saving due to Redux bonding were more than 25 per cent., the riveted tabs must have been badly designed. If the saving in main control surface mass balance were more than three times the saving in tab weight, the control

surfaces were inefficiently mass balanced. If the original riveted tab were well designed, he thought the weight saving due to Redux bonding might be only half that given, *i.e.* 20 lb. an aircraft. Even this was a weight saving worth having. In addition, the Redux tabs should have a better external appearance, and a higher fatigue strength, than the riveted design.

Good as Redux was, a better adhesive could be imagined. The two improvements which the aircraft manufacturer would most like to see were:—

1. A satisfactory cold-setting adhesive. The heating to 140°C.-150°C. was the greatest single source of difficulty and trouble in the Redux process.

2. An adhesive which maintained a high strength at elevated temperatures (up to 100°C.). The loss in strength of Redux joints at those temperatures (although its seriousness should not be exaggerated), did impose some limitations on the use of Redux.

J. K. Crowe (de Havilland Aircraft Co. Ltd., *Assoc. Fellow*), *contributed*: In considering the use of Redux in aircraft structures, it must be remembered that the application of any new assembly process in large scale production was very different from its application in the laboratory, and a great deal of costly development work (often including the design of suitable plant and equipment) had to be done before it became a useful and reliable production tool.

In any case, no new assembly process could be introduced into a factory without the full co-operation of the production management and personnel.

Among the advantages of the Redux system over other forms of assembly were: (*i*) Improved compressive strength with consequent saving in weight (which seemed to apply over a wide range of skin thicknesses, provided the panels were correctly designed and the Redux joints soundly made); (*ii*) Improved fatigue strength; (*iii*) Smooth finish—when the heat distortion problems had been overcome; (*iv*) Saving in production cost and production time on mass-production batches, when the initial development work had been completed, and when the cost of that work and of the necessary plant and equipment had been paid. In this connection, the number of rivets eliminated could easily run into many millions on a production batch of panels.

Experience indicated that Redux was satisfactory under extreme climatic conditions. Doves had been operated successfully over a considerable period of time in both hot and cold climates, including Canada, Australia, Africa, India and the Middle East. There was also a good deal of other evidence in this connection.

In providing a continuous joint between structural members in high strength aluminium alloys, the Redux process fulfilled a long-felt want, especially in the Aircraft Industry, and made a real contribution to improvement in structural design. Its scope was very wide and no doubt its application would continue to increase in the future.

MR. MOSS'S REPLY

Mr. Hancock: The inspection of glued joints was always a difficult problem but he was not convinced that it was any more difficult than the inspection of spot-welded or riveted joints. At present they recommended the following methods:

(*a*) A "peeling" test should be carried out on specimens which had gone through the bonding process with each aircraft panel. As this test, in which two strips of metal were "peeled" or "stripped" apart, was an exceptionally sensitive one it would immediately show up any deficiences in the degreasing and pickling of the metal, as well as in the actual bonding operation. Not much reliance should be placed on control tests on shear specimens because it was comparatively easy to obtain good shear strength on Redux joints.

(*b*) In addition, the degreasing and pickling plants should be subjected to frequent checks to ensure that they had neither become contaminated nor lost strength. Metal after pickling was always washed in running water to ensure that no contamination occurred.

All those operations should be watched by an inspector. The pyrometers and pressure gauges on hydraulic presses or autoclaves should be checked at weekly intervals and, where possible, recording instruments should be used. Inspectors should record the temperature and pressure at which each bonding operation was made so as to ensure that they were properly supervised.

(*c*) After completion of the bonding, panels should be examined to see that some

Redux liquid and powder had been forced out of the joint, thereby providing evidence that sufficient adhesive, heat and pressure had been applied. The material at the edges of the joint might vary from a light colour to reddish brown. If it were dark brown or black the joint was over-cured and would be brittle.

(*d*) When thin veneers had been bonded to metal the adhesion should be tested by complete immersion of the assembly in water. If the bond were poor the well-soaked veneers would soon form blisters, but if the adhesion were good they would not do so.

The combination of the "peeling" test with the other methods mentioned would give a satisfactory check on all production bonding.

Many efforts had been made to find non-destructive methods for inspecting bonded panels but, so far, none had given promising results. At his suggestion, the A.I.D. Headquarters at Harefield had investigated supersonic methods for testing glued joints between metals but without much success.

In general Redux joints did not require any supplementary riveting or screwing. The only exception was that where thin metal components were bonded together, rivets might be put at the ends of the joints to prevent "peeling" occurring in rough handling. For example, if a thin skin were bonded to stiffeners it was good practice to use a rivet at the end of each stiffener. With thick materials this was unnecessary because the tendency for "peeling" to occur was so much smaller.

Redux was quite a good electrical insulator and electrical bonding must be carried out quite separately.

The successful operation of the Comet was the best evidence that no difficulties arose due to low temperatures of flight.

Mr. James: He thought that the points raised by Mr. James were an excellent statement of the need for far more research on Redux-bonded structures! So far only a very limited amount of work had been done and there was scope for much more research to investigate more thoroughly the design of bonded structures. It was possible that in lighter panels bonding would have a bigger advantage than in heavier ones but it was significant that de Havillands had used Redux throughout the skin and fuselage of the Comet, which was a fairly large aircraft in which, presumably, fairly thick skins had to be used. He imagined that the panels referred to by Mr. James were those tested by Vickers-Armstrongs Ltd. He had not the results in detail but believed that all the Redux-bonded panels gave appreciably higher results than the corresponding riveted ones, except for one in which the riveted panel was slightly superior. He believed that it was true that even with some of the heavier panels the superiority of Redux was quite marked. He had now heard that the College of Aeronautics had tested some Redux-bonded panels having skins varying from 16 to 20 s.w.g. and every one of them was stronger than the corresponding riveted panel. However, he felt that the main conclusion was that far more systematic work was required to investigate the strength of Redux-bonded panels of various thicknesses.

With regard to the distortion occurring during bonding at 145°C., he knew that some did occur but their experience was that it could usually be reduced to far less than that which occurred with riveting and spot welding. He would have thought that 145°C. was hardly a high enough temperature for much "stress relieving" to take place.

Mr. Giddings: In bonding stringers to a skin in a steam-heated press the skin was usually in direct contact with the lower platen of the press, whereas the stringers were always a short distance from either the upper or the lower platen. After bonding was completed the press was cooled by passing cold water through the platens, and the skin, which was actually in contact with the platens, might cool a little more quickly than the stringers. If this did occur then the panel would be "bowed" laterally when taken from the press but if care were taken to ensure that the stringers were not unnecessarily distant from the top platen of the press (due, for example, to the use of thicker jigs than necessary) and if cooling were not carried out too precipitately, then no such distortion would occur. He was quite certain that distortion arising in this way had been the cause of some of the lower results obtained with Redux-bonded compression panels and was equally certain that it was a difficulty which was easily overcome as experience in carrying out the process was gradually acquired. Perhaps it was an example of what the Americans referred to as "know-how"!

The shear strength of a Redux joint did fall at temperatures above 60-70°C. but it

was at least equally important that there was no such loss in peeling strength until at least 90°C. In fact there might even be a slight increase in peeling strength up to this temperature.

He had dealt with inspection procedure in replying to Mr. Hancock but would like to add that even though it might not be possible to interpret the results of the "peeling" test as design data, it was nonetheless a very searching "quality control" test and there was no evidence to suggest that specimens which were inferior in any way would pass it. It might even establish an unnecessarily high standard but he had much rather that for the present the error was in that direction.

It was interesting that the Redux bonding of Dove components had proved cheaper than riveting would have been but it was difficult to generalise from that example. Much depended on the design of the components and their suitability for bonding but it must always be remembered that holes for rivets were drilled and countersunk individually and that the rivets must be put in one at a time, whereas with a gluing process a large area could often be bonded in much the same time as a smaller one.

Mr. Tyson: He agreed with Mr. Tyson's statement of the advantages of Redux bonding, particularly his remarks on the fatigue properties of riveted and bonded structures. Naturally a cold-setting adhesive would prove useful but it had not proved an easy matter to develop such an adhesive which would give bonds which were sufficiently strong both at normal and at elevated temperatures and which were also sufficiently resistant to petrol, paraffin, lubricating oil, de-icing fluids, and so forth, and, perhaps more important, to prolonged exposure to the weather in any part of the world. It must also be remembered that the advantage of a resin setting at room temperature might well be offset by the long time required for the curing of such a resin. An example of that might perhaps be found in the glues used for making wooden aircraft. Although they gave satisfactory results when cured at room temperature, many aircraft manufacturers found it worth while to accelerate their curing by raising the temperature. Another example might be found in the manufacture of plywood, where hot and cold-setting glues were both freely available but where, in practice, hot setting glues were always used.

The explanation of the weight saving on the servo control tabs made by the Bristol Aeroplane Co. Ltd. was as followed: The direct weight saving on the various tabs was approximately 15 lb. due to changing from riveting to Redux bonding. The saving on the balances for the tabs in the controls was about three times that weight, *i.e.* 45 lb., giving a total of 60 lb. This in turn might result in a saving in the balances for the controls of about three times that weight, *i.e.* 180 lb. Thus the total might be about 240 lb. Those figures were approximate but they did indicate the weight saving which might occur by using Redux on servo control tabs.

Mr. Crowe: Mr. Crowe and his company had had such a long and varied experience with Redux, he appreciated his remarks.

A NOTE ON THE TIME REQUIRED TO MAKE A LEVEL SPEED MEASUREMENT WITH A TURBINE-JET AIRCRAFT

by

K. J. LUSH, B.Sc., D.I.C.

SUMMARY

It was desired to confirm quantitatively pilots' impressions that on turbine-jet aircraft in the region of 40,000 ft. the level speed stabilised very slowly.

The time required to make a conventional level speed measurement has been examined, for a representative turbine-jet aircraft, over a wide range of air speed and height. The results are compared with those for a typical piston-engined aircraft and their implications discussed.

It is concluded that the time required to make a conventional level speed measurement increases rapidly with height, in the absence of compressibility effects on drag, and is about five times as great at 40,000 ft. as at sea level. It is inconveniently large at high altitude and level speed measurements there will require very long runs, unless it is arranged that each run is started at an air speed near the steady level speed.

This increase will be present in most level speed tests, especially those in the region of the best speed for range. In maximum level speed measurements, however, compressibility effects may be present and the air speed may then be expected to settle down quickly.

The need for long runs at high altitude is not peculiar to jet aircraft, but has come into prominence concurrently with them.

NOTATION

$a = -\dfrac{d}{dV}\left(\dfrac{dV}{dt}\right)$ at $V = V_0$

D = aircraft drag

e = base of natural logarithms

g = acceleration due to gravity

H = height of aircraft above some arbitrary datum

K_F = ratio of speed to minimum power speed ($= \sqrt[4]{3\lambda}$)

$(L/D)_{max}$ = maximum lift/drag ratio

T = engine thrust

t = time

t_R = relaxation time (minutes)

V = true air speed

V_0 = steady level speed

V_{imd} = equivalent air speed for minimum drag

W = aircraft weight

$Y = (V/T)(dT/dV)$, the variation of thrust with speed at the stabilised speed

λ = ratio of stabilised air speed to speed for minimum drag

σ = ratio of density to standard sea level density.

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1. INTRODUCTION

Pilots making level speed measurements on turbine-jet aircraft at heights in the region of 40,000 ft. have commented on the length of time required for the air speed to stabilise. It was desired to investigate this feature analytically. This is done below, with the aid of the following two concepts:—

(*i*) *steady level speed*—the air speed at which the longitudinal acceleration in rectilinear level flight is zero.

(*ii*) *relaxation time*—the period over which the difference between the air speed and the steady level speed falls to $1/e$ of its initial value.

The time required to make a conventional level speed measurement is roughly assessed

in terms of the relaxation time. The relaxation time is calculated for a typical turbine-jet aircraft for a wide range of height and true level speed, and compared with that for a typical piston-engined aircraft. The implications of the results are discussed.

2. THE TIME REQUIRED FOR A LEVEL SPEED MEASUREMENT AS A PROPORTION OF THE RELAXATION TIME

When making a level speed measurement a rough estimate is first made of the steady level speed to be expected. Starting at an air speed near this estimate, the aircraft is then flown at constant altimeter reading until the air speed settles down to a value at which it remains sensibly constant for a period of one to five minutes, the period chosen depending on the rapidity with which the air speed settles down. This value is then taken to be the true level speed. The time required thus depends on the accuracy of the initial estimate and on the acceleration available.

The difference between the aircraft's instantaneous air speed and the steady level speed decays exponentially if the initial difference is not large. An indication of the rapidity with which the speed settles down therefore is given by the relaxation time.

In the absence of a special technique the initial difference between the air speed and the steady level speed will usually be of the order of 5 per cent. and the run will usually be continued until this difference has fallen to about 1/3 per cent. If t_R minutes is the relaxation time the speed will then have changed by only $(e-1)/3$ per cent., *i.e.* by about 0.6 per cent., in the last t_R minutes.

Unless special steps are taken to ensure that each run is started at an air speed near the steady level speed, the time required for a level speed measurement is approximately that in which the difference between the air speed and the steady level speed will fall to one-fifteenth of its initial value. That is, the time required is approximately $t_R \log_e 15$, or about 2.7 t_R minutes. A good idea of the time required to make a level speed measurement is thus obtained by assuming it to be three times the relaxation time. Of this time only the last half would be used as a basis for estimating the true speed. The first half would be disregarded as unstabilised. The error involved in the estimate of the mean speed would be slightly less than twice the difference between the final speed and the true steady level speed, *i.e.* on the foregoing basis, about 1/2 per cent.

3. MATHEMATICAL RELATIONS

Over the small speed range with which we are concerned we write

$$dV/dt = -a(V - V_0) \quad . \quad (1)$$

where

$$a = -\frac{d}{dV}\left(\frac{dV}{dt}\right) \text{ at } V = V_0 \text{ and is positive.}$$

Hence the relaxation time t_R is given by

$$60\, t_R = 1/a. \quad . \quad . \quad (2)$$

It is shown in the Appendix that in the absence of compressibility effects on drag

$$\frac{1}{a} = \frac{2V_{imd}}{\lambda g\sqrt{\sigma}}\left(\frac{L}{D}\right)_{max}\left(1+\frac{g}{V}\frac{dH}{dV}\right)\times \times \left\{\frac{1}{(2-Y)-\frac{1}{\lambda^4}(2+Y)}\right\} \quad (3)$$

4. RANGES OF VARIABLES

The equivalent air speed for minimum drag is usually in the range 200 to 300 ft./sec. λ is always greater than unity in level speed measurements and ranges between about 1.3 at the optimum speed for range and about 3 at high speed at low altitude. $(L/D)_{max}$ is normally between 10 and 16. The term

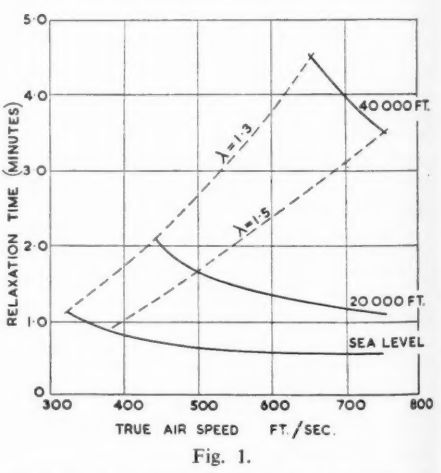


Fig. 1.

Variation of relaxation time with height. Typical jet aircraft.

TABLE I.

RELAXATION TIMES FOR TYPICAL TURBINE-JET AIRCRAFT

Height	$1/\sqrt{\sigma}$	λ	*True air speed (ft./sec.)*	$\frac{g}{V}\frac{dH}{dV}$	Y	t_R *(minutes)*
Sea level	1	1.3	325	0.08	−0.8	1.13
		1.5	375	0.06	−0.7	0.90
		2.0	500	0.04	−0.6	0.66
		2.5	625	0.06	−0·3	0.59
		3.0	750	0.06	+0.1	0.58
20,000 ft.	1.370	1.3	445	0.08	−0.3	2.10
		1.5	514	0.06	−0.2	1.60
		1.8	616	0.05	−0.1	1.36
		2.0	685	0.04	+0.1	1.26
		2.2	754	0.05	+0.1	1.08
40,000 ft.	2.015	1.3	654	0.08	+0.1	4.51
		1.4	704	0.07	+0.2	3.93
		1.5	754	0.06	+0.3	3.50

$(g/V)(dH/dV)$, which arises from the change in height with air speed due to position error changes when accelerating at constant altimeter reading, lies in the range from -0.2 to $+0.1$ approximately. It varies with equivalent air speed, for a given aircraft, but is sensibly independent of height.

Y will lie approximately in the range from -1.0 to $+0.5$. It is large and negative at low engine speeds and low altitude but increases with engine speed and altitude. Note that over a small range T varies as V^Y.

5. AN EXAMPLE

As an example a hypothetical fighter has been considered which was similar to the Meteor Mk. 4, and for which the following values were taken: $V_{imd}=250$ ft./sec., $(L/D)_{max}=12$.

The values of $(g/V)(dH/dV)$ (at constant altimeter reading) and of Y have been assumed to be the same as for the Meteor Mk. 4.

With these assumptions the relaxation time t_R has been evaluated and is presented in Fig. 1 and Table I. It will be seen that its value at 40,000 ft. is large, being about five times as great as that at sea level even at the same value of λ. This difference will be increased in practice by the fact that rather lower values of λ are of interest at high altitudes than near sea level.

Of the five-fold increase, about half is due directly to the decreased density of the air, which increases the change in true speed required to bring about a given change in equivalent air speed*. The remainder of the increase is due to the increase in Y, the rate of variation of thrust with air speed (*cf.* Section 4). For example it will be seen that, at a λ of 1.3, Y is -0.8 at sea level, so that thrust varies as $V^{-0.8}$ whereas at 40,000 ft. Y is $+0.1$, so that thrust varies as $V^{0.1}$.

6. COMPARISON WITH PISTON-ENGINED AIRCRAFT

The problem is discussed for piston-engined aircraft in reference 1. Relaxation times for a typical piston-engined aircraft may be deduced from Fig. 39(*b*) of that reference, in which $\sqrt{\sigma}\, t_{0.1}$, which is $60\, e\, t_R\sqrt{\sigma}$, is plotted† against K_Y, which is $\lambda \times \sqrt[4]{3}$. K_Y will lie between 1.3 (for best range) and about 2.5 (at high speed at low altitude). Relaxation times so deduced are given in Table II; it is sufficient to remark here that they are of the same order as those for the turbine-jet aircraft.

*The drag at a given equivalent air speed, in the absence of compressibility effects and so on, will be independent of height.

†The vertical scale of Fig. 39(*b*) is in error, and the figures read off for $\sqrt{\sigma}t_{0.1}$ should be multiplied by 10.

7. DISCUSSION

It is believed that the example of Section 5 is typical and that the large increase of relaxation time with altitude will be encountered on all turbine-jet aircraft in the absence of compressibiliy effects. It will thus be present in most level speed tests, other than measurements of maximum level speed. In particular, it will be present at speeds in the region of the best air speed for range. When, however, compressibility effects on drag are present the associated rapid rise of drag with increase of air speed will tend to produce rapid stabilisation at all altitudes.

It follows that conventional level speed measurements at altitudes of the order of 40,000 ft. will often require very long runs, of the order of 15 minutes, unless it can be arranged that each run is started at a speed very near the steady level speed. In a research investigation in progress at the A. & A.E.E. this is being attempted by adopting a special test programme. An air temperature measurement is first made and a series of level speed runs is then made at engine speeds so chosen by reference to the observed temperature as to give, approximately, pre-determined indicated air speeds. The pilot is given a card from which he chooses his engine speeds according to the range in which the observed temperature falls and he arranges that each run is started at an air speed near the estimated steady speed.

This method requires some knowledge of the performance of the aircraft, which may be obtained from preliminary tests; it may not be the best for routine work, and a re-assessment of the relative suitability of the conventional and other test techniques seems desirable.

The long level speed runs required at these high altitudes have not presented a serious problem until recently because level speed measurements at such heights (of the order of 40,000 ft.) have rarely been required. With the general increase in operating altitudes, however, they have come to form an essential part of performance tests on high altitude fighter aircraft, and may be expected to continue to do so for some years. With jet aircraft, range tests at these altitudes are also necessary, because operation near the cruising ceiling, for such aircraft, is essential to the achievement of a range performance near the optimum.

TABLE II.

RELAXATION TIMES FOR TYPICAL PISTON-ENGINED AIRCRAFT

Height	K_V	*True air speed (ft./sec.)*	t_R *(minutes)*
Sea level	1.3	189	2:12
	2.0	292	0.78
	2.5	364	0.58
20,000 ft.	1.3	260	2.90
	2.0	398	1.07
40,000 ft.	1.3	381	4.28
	2.0	585	1.57

8. CONCLUSIONS

In a level speed measurement the aircraft air speed approaches the steady level speed exponentially, and unless special steps are taken to ensure that the run is started at a speed very near the steady level speed, the run must be maintained for about three times the corresponding relaxation time to obtain a satisfactory indication of the steady level speed.

The relaxation time for a level speed run with a turbine-jet aircraft varies rapidly with height, being about five times as great at 40,000 ft. as at sea level. In consequence, the conventional level speed measurement technique involves inconveniently long runs at high altitudes.

The time required can be reduced by arranging to start the run at an air speed very near the steady speed. This, however, complicates the test routine and necessitates some knowledge of the performance of the aircraft from preliminary tests or from other sources. A re-assessment of the suitability of the conventional and other test techniques therefore seems desirable.

The long relaxation times at high altitude are not peculiar to the jet aircraft, but performance measurements at such heights have not been required frequently in the past. They will, however, be essential to a satisfactory knowledge of the performance of a fighter during the next few years.

It is proposed to re-assess the merits of the various performance techniques for turbine-jet aircraft.

REFERENCE

1. ANNAND, W. J. D. The Range of Reciprocating Engined Aeroplanes. A. & A.E.E./Res./235.

APPENDIX

THE VARIATION OF ACCELERATION WITH AIR SPEED

We have $$\frac{W}{g}\frac{dV}{dt} = T - D - \frac{W}{V}\frac{dH}{dt} = T - D - \frac{W}{V}\frac{dH}{dV}\frac{dV}{dt}.$$

i.e. $$\frac{dV}{dt}\left(1 + \frac{V}{g}\frac{dH}{dV}\right) = g\left(\frac{T}{W} - \frac{D}{W}\right).$$

If it is assumed that, for flight at constant altimeter reading, $(g/V)(dH/dV)$ is independent of air speed over the relatively small range with which we are concerned, then

$$\left(1 + \frac{g}{V}\frac{dH}{dV}\right)\frac{d}{dV}\left(\frac{dV}{dt}\right) = \frac{g}{W}\left(\frac{dT}{dV} - \frac{dD}{dV}\right).$$

Also, as we are concerned with a small range of speed about the steady level speed and a small range of height it may be assumed that

(*i*) $T = D$ approximately

(*ii*) the air density is approximately constant.

Hence $$\frac{1}{W}\frac{dT}{dV} = \frac{D}{W}\frac{1}{V}\frac{V}{T}\frac{dT}{dV} \quad \text{approximately}$$

$$= \frac{1}{(L/D)_{\max}}\frac{1}{2}\left(\lambda^2 + \frac{1}{\lambda^2}\right)\frac{Y}{V}.$$

Also, $$\frac{1}{W}\frac{dD}{dV} = \frac{1}{V}\frac{1}{(L/D)_{\max}}\frac{V}{D}\frac{dD}{dV}\frac{1}{2}\left(\lambda^2 + \frac{1}{\lambda^2}\right)$$

$$= \frac{1}{V}\frac{1}{(L/D)_{\max}}\left(1 - \frac{2}{\lambda^4 + 1}\right)\left(\lambda^2 + \frac{1}{\lambda^2}\right).$$

Hence

$$\frac{g}{W}\left(\frac{dT}{dV} - \frac{dD}{dV}\right) = \frac{g}{(L/D)_{\max}}\frac{1}{2V}\left(\lambda^2 + \frac{1}{\lambda^2}\right)\left(Y + 2 - \frac{4}{\lambda^4 + 1}\right)$$

$$= \frac{g}{(L/D)_{\max}}\frac{\sqrt{\sigma}}{2\lambda^3 V_{\text{imd}}}\left\{(Y+2)(\lambda^4+1) - 4\right\}$$

$$= \frac{g}{(L/D)_{\max}}\frac{\sqrt{\sigma}}{2\lambda^3 V_{\text{imd}}}\left\{Y(\lambda^4+1) + 2(\lambda^4 - 1)\right\}$$

$$= \frac{g}{(L/D)_{\max}}\frac{\lambda\sqrt{\sigma}}{2V_{\text{imd}}}\left\{(2+Y)\frac{1}{\lambda^4} - (2-Y)\right\}.$$

Therefore if t_R is the relaxation time in minutes

$$60t_R = 1/a \quad \text{(Section 3)}$$

$$= -\left[\frac{d}{dV}\left(\frac{dV}{dt}\right)\right]^{-1}$$

$$= \frac{2V_{\text{imd}}}{g\sqrt{\sigma}}(L/D)_{\max}\left(1 + \frac{g}{V}\frac{dH}{dV}\right)\left\{\frac{1}{2 - Y - (1/\lambda^4)(2+Y)}\right\}.$$

REVIEWS

FLUID PRESSURE MECHANISMS. H. G. Conway. Sir Isaac Pitman & Sons Ltd. London. 1949. 218 pp. Diagrams. Index. 25s. net.

There are very few publications dealing with hydraulic and pneumatic systems in aircraft and this book is a notable addition to their number, particularly as the author has a long personal experience in this specialised section of aircraft engineering.

It would clearly be impossible to compress a general text book on these two subjects within the compass of little more than two hundred pages and the author has chosen, as the title indicates, to concentrate on diagrammatic representation of components and systems by reducing the variations and complexities of individual designs to their simplest fundamental mechanical form. Some of these mechanisms are well known, others may have only limited use, but in total they represent the available paths along which a designer may seek the required solution to his problems.

This process not only simplifies but also clarifies a complex subject and in addition it stimulates creative thought by showing clearly how the fundamental elements of a known design can be re-arranged in another way.

The subject is dealt with from first principles and there is no doubt that the book will be as useful to the student who knows little of the subject and is anxious to build on firm foundations, as to the specialist who is already familiar with the basic principles but who will certainly find it a most useful means of reference for a wide variety of purposes.

The book is divided into two parts, the first of which deals with the mechanism of individual components, the second being devoted to description of the way in which they are combined to form complete systems. In both cases it is necessary that the text should be profusely illustrated and this is most adequately covered by well over five hundred diagrams.

In the text every effort has been made to avoid showing undue partiality for one mechanism over another and as a consequence, as the author himself points out in his preface, there is no tendency to reflect contemporary design fashions. This is likely to increase the value of the information given over a period of years, particularly if any additions which may be found necessary are made in future editions, which will doubtless be justified.

Here in a concise and convenient form is a wealth of information which would otherwise have to be compiled from analysis of contemporary design and a careful search of patents and text books. It is likely to be of equal value to the specialist as a work of reference and also to those in other branches of aircraft engineering who have a need for a good general knowledge of these subjects, either as designers or users.—S.M.P.

SUPERSONIC AERODYNAMICS—A THEORETICAL INTRODUCTION. Edward R. C. Miles. McGraw-Hill. 1950. 255 pp. Diagrams. Index. 34s. net.

Although there are several good text books on supersonic aerodynamics available, the field is far from being adequately covered and there is ample room for new treatments and new selections of materials. Thus any new book on the subject is to be welcomed. In considering this book attention must be drawn to the subtitle, which needs some expansion and explanation. It is, in fact, a theoretical introduction to the problems of the flow of a perfect fluid and the reader will not only find no application to the problems of aircraft, but will find no mention of a boundary layer and no hint of the way in which viscous effects can cause the flow to break down in real cases. This limitation of scope is quite justifiable. However, in other books on the subject the chapters covering these points have been the

weakest section and there is a real need for an adequate discussion of these points. (Possibly some of these points may be dealt with in Bonney's "Engineering Supersonic Aerodynamics" due from the same publishers.)

Although the approach is entirely theoretical, this is not a mathematician's volume. A main feature of the book is that a full mathematical training is not assumed on the part of the reader and most engineers working in or near this field will find the book quite readable and will welcome the detail given in the mathematical analysis.

After a general introduction (developing the concepts of divergence, circulation and the potential function) the application of the method of characteristics to two-dimensional and axially symmetric flow is described, the latter being dealt with in some detail—more than its practical usefulness may warrant. The linear theory is also developed and applied again to two-dimensional aerofoils and bodies of revolution. Here one might wish for some examples of the application to aerofoils of finite aspect ratio. The book is completed by a good chapter on the flow past cones, a discussion of shockwaves, omitting shock intersections, a chapter on the hodograph transformation dealing mainly with Chaplygin's work and a chapter comparing flows with shocks with comparable isentropic flows, which emphasises usefully the small effects of entropy change with the weak shocks usually encountered with thin wings and slender bodies. There is some confusion in places in the discussion of the physical background, for example the introduction to the chapter on shock waves is very confused.

The author makes a special point of the examples but these, which vary from triviality to considerable difficulty, seem to be more tests of algebraic manipulation than of aerodynamic understanding. They will be of more use to students than to aeronautical engineers. The numerical values of the various functions of the ratio of the specific heats appearing in the equations are used throughout, which seems a pity. Few misprints have been found and the only one which might cause confusion is the writing of "pressure ratio" for "pressure coefficient" in Fig. 69.

This book is not a complete course in supersonic aerodynamics, but it covers an essential part of the field and despite the detailed criticisms which have been made, manages to be essentially readable and it deserves to be widely read.—L.F.N.

PROPERTIES OF METALS AT ELEVATED TEMPERATURES. George V. Smith. McGraw-Hill, New York and London. 1950. 400 pp. 236 figures. Appendix. Index. $7.00 net.

Since the end of the Stone Age, not merely until today, but for an unmeasured and unmeasurable period yet to be, the development of material civilisation has depended and will mainly depend on man's increasing mastery of the chemistry and physics of metals. Mechanical power, either direct from heat engines or by way of the agency of electricity has, by its very economy in human effort, done more than the humanitarians themselves to liberate mankind from the shackles of manual labour.

Today, when electricity, surely the greatest of the liberators, is being produced by turbine units of 100,000 and more horse power, using steam at over 1,000 lb./in^2., at a superheat of more than 500°C., ever-increasing demands are being made upon the metallurgist, while the further growth of the Cinderella of power plants, the gas turbine, depends at least as much on him as upon the mechanical engineer.

Such being the position, it is both fitting and opportune that George V. Smith, of the Research Laboratory of the United States Steel Corporation, should give us a book at this time on the properties of metals at elevated temperatures, but has he given us the right book? In the opinion of the reviewer, he has done a good job, but has attached quite the wrong title to it. Were this erudite, well-written and excellently produced work called "An Introduction to the Study of Metallic

Materials at High Temperatures" this would far more adequately describe its contents.

The first six chapters constitute a sound review of current ideas on such aspects of metal physics as the general principles of plastic flow, creep and fracture. A chapter on testing follows and after this there is some practical information in relation to ferrous and non-ferrous alloys. What is said of the former is more satisfying than that which relates to the latter, while as regards the aluminium alloys the author is somewhat inadequate.

A reader requiring a treatise on some aspects of physical metallurgy will find this work worth while. On the other hand, a mechanical engineer hoping to get help in the solution of some high temperature problem, will find it a disappointment. Finally, the index will give satisfaction to nobody—to omit both Nimonic and Inconel in the index of a work on high temperature materials is surely an example of mental aberration *in excelsis*? It is but fair to add, however, that the author deals in the text with both alloys.—P.L.T.

INTRODUCTION TO HELICOPTER AERODYNAMICS. W. Z. Stepniewski. Rotorcraft Publishing Committee, Morton, Pennsylvania, U.S.A. 1950. 158 pp. $2.00 net.

Volume I on Performance is the first of a series of booklets which the Rotorcraft Publishing Committee is preparing with the object of advancing the theory, design and practical development of rotary wing aircraft. Subsequent volumes will cover Blade Dynamics, Air Loads, Stability and Control, and Helicopter Design.

The first quarter of Volume I gives a simplified presentation of the fundamentals of aerodynamics. Mathematical complexity is omitted, a selected list of references being appended for those who may wish to make detail studies, with the result that mechanical engineers will read the subject matter with appreciation. The usefulness of the concept of circulation around an aerofoil and of Conformal Transformation are typical of the subjects which are explained quite simply. The characteristics of laminar flow aerofoils and the influence of Mach number on force and moment coefficients are described.

The second quarter of the book is devoted to the three classic theories of the propeller—Simple Momentum, Blade Element and Vortex. Here again attention is directed mainly to the underlying physical principles and not to mathematical manipulation. A discussion of these theories forms an excellent background for the student in his approach to the problem of vertical flight.

It is in the third quarter of the book that this problem is met. Here the significance of the basic parameters of the rotor is what the author wishes to establish and he achieves his aim by simple logic. The complete absence of charts and lengthy numerical calculations clears away from the reader's eyes irrelevant matter which would merely confuse the issue. References are provided at each chapter for those whose appetite has been whetted and who wish for more.

Finally, the last quarter extends the theory to cover forward flight, both powered and auto-rotative. Part of what is included usually under the term "profile power" is considered as a contribution of the rotor to the parasite power. This is cited only as one of many physical interpretations which permeate the whole volume and enhance its attraction to the reader. The descriptive paragraphs on auto-rotation are clear and precise.

The book, besides presenting ably and authoritatively the fundamentals of rotary wing theory, is fluently written and attractively illustrated. It thus requires little effort to follow the absorbing story from cover to cover and the reviewer looks forward to the next instalment of the serial. The author's intention is to capture the interest of the mechanical engineer and the young graduate and it is to these and others of similar technical training that such literature will make its strongest appeal. The low price of $2.00 reflects the Committee's policy of publishing the series on a non-profit making basis.—J.A.J.B.

HANDBOOK OF AERIAL MAPPING AND PHOTOGRAPHY. Major Trorey. Cambridge University Press. 1950. 178 pp. Illustrated. 25s. net.

Those who knew Major Trorey during the German Campaign will be glad to see that he has made available the very valuable Air Survey technique and methods which were developed by him to compete so successfully with the phenomenal mapping demands of the Army. For those concerned with the running of an air survey organisation the book presents a very clear picture of the essentials of theory and practice required to ensure an efficiently run map-making machine.

Dealing with the subject matter of the book in detail there are a few comments one might make.

The author has devoted the first four chapters out of a total of eleven to the subject of Obliques. No doubt the Canadians are in the fore-front of the development of oblique technique, and Major Trorey produced some valuable results with his oblique methods, particularly for study of the height of river banks during the advance into Germany, but the further development of modern photogrammetric technique is unlikely to derive anything more of value from oblique methods, and in a book of this type study of such methods could be omitted without great loss to the value of the rest of the book.

The chapter on Parallax is good. It is just that little bit more than "Parallax without Tears" which makes it valuable to the operator meeting the subject for the first time, and will put him in the position of being able to solve for himself most of the problems which are so perplexing to the untrained inexperienced photogrammetrist.

On Page 91 a few words are devoted to the subject of Motion Aberration. Major Trorey has in the past cleared away many of the practical difficulties encountered in Photogrammetry. He might now turn his mind to a study of Motion Aberration as one of the few remaining obstacles to the further development of Air Survey technique for large scale mapping. On the subject of obvious omission, one might further say that the author only lightly considers the question of the influence of Film Distortion on the accuracy of the finished map. Here he might find a field of valuable study in considering how to get rid of one of the last of the bugbears of the seeker after more accuracy in Photogrammetry.

There is no Royal Road to proficiency in Radial line plotting, but the author has concentrated on stressing the essential practical points of the technique in his treatment of the subject, and the drill has been reduced to its simplest terms without saying too much on the technical side.

In dealing with the slotted template the author very wisely says "the problem . . . . will be understood by laying a block better than by description," but there are so many practical difficulties which may be encountered before and during the laying down of the block that this subject might have been usefully treated more fully. Incidentally, the "Zero Adding Section" has been busy on the caption to Fig. 63 and the reference to the figure on Page 105—500 sq. km. are hardly worth controlling by Slotted Template methods!

While there is no doubt that there will always be a need for an instrument for carrying out precise rectification of photographs, and there is equally no doubt that the Trorey Anharmonic Rectifier is probably the most efficient of the instruments which can be used to do quick rectification in the drawing office, it is important to bear firmly in mind the wide difference between the two types of instrument. It is suggested that, too often, potential users of Air Photographs have been led to expect too much from maps prepared by the use of the simpler type of rectifier, with the result that faith in the accuracy to be obtained from Air Survey methods has been largely shaken.

The remaining part of the book, which deals with the practical side of making maps, is the most valuable. In particular, Appendix I which is obviously a straight reprint of Major Trorey's War-time Instructional Manual, gives the results of the author's successful experience in training a team in photogrammetry from scratch.

The Appendix shows signs of hasty editing and would well have repaid the effort of writing in clearer English. On Page 153, Para. 3/252, reference is made to the "Benson Area." No doubt many of us will get a nostalgic pleasure out of seeing the words now in somewhat happier circumstances, but it is doubtful if future operators will understand what the phrase means in a manual of Photogrammetry!

But despite these somewhat facetious criticisms, the whole treatment of the subject of teaching the operators is extremely valuable and no one can deny that by his teaching methods the author certainly produced very fine results.—A.P.

CORRESPONDENCE

ELEMENTARY ASPECTS OF TECHNICAL STATISTICS

There is something in the paper "Elementary Aspects of Technical Statistics and Common Fallacies" by Mr. W. E. Thornton-Bryar (July 1950 JOURNAL) which I do not understand:

P. 470—80 aircraft. 41 engines replaced in six months.

(*a*) 41 replacement engines is just under seven a month not just over eight.

(*b*) The calculation based on percentage of engines at risk is surely misleading. The formula

$$\frac{41}{121} \times \frac{100}{6} = 5.65 \text{ per cent. a month}$$

can be written

$$\frac{Kn}{Kn+80} \times \frac{100}{n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where n = the number of months in the observational period and K a constant (in the example ≈ 7).

The expression (1) tends to zero as n tends to infinity.

Thus for a 12 months' observation period we have

$$\frac{82}{162} \times \frac{100}{12} \approx 4.2 \text{ per cent.}$$

for a one month period

$$\frac{6.85}{86.85} \times 100 \approx 5.9 \text{ per cent.}$$

The air crew work is to change about seven engines a month and no percentage calculation alters this. The spare engines cannot be estimated without much more information but this equally cannot be affected by the observational period, except in so far as a longer period gives greater precision to the estimate and hence reduces the number required for any *confidence* level.

John D. North, *Fellow*

Mr. Thornton-Bryar's paper on "Technical Statistics and Common Fallacies" would be of so much interest to present and past members of the Royal Air Force, that it was a pity he said nothing about the history of aero-engine reliability statistics in that Service, and how they originated.

During the 1939-45 War, the approved service lives of military aero-engines were promulgated to Commands and lower formations by the Air Ministry, but Commands had the power to vary these "lives between overhauls" as a result of their operating experience. For the first four years of the War, any such variation was done largely as the result of strip examination of such engines as managed to run their full life: if a reasonable number of engines stripped in good condition, that was a fair indication that the service life could be increased, and no attempt was made to study the incidence of engine failure as a function of hours run since new or since complete overhaul.

During the rapid expansion of Bomber Command in 1943, the Command engineer staff found themselves between two opposing factions, with the squadron engineer officers objecting most strongly to the unreliability of completely overhauled "Whistler" engines and the repair organisation maintaining that the overhauled engines were every bit as good as new "Whistlers" of similar mark. The only way to determine who was right was to saddle the harrassed squadron engineer officers with yet more paper work by making them segregate the monthly flying times of aircraft by mark of engine installed (and there were six different engine marks concurrently in use in one type of heavy bomber), in order that the monthly flying times of every engine mark/aircraft combination might be determined. At the same time, a quarterly return showing all engines installed by mark and age group was instituted; also, a monthly return of engine changes, classified in groups similar to the author's Table VI. From this information, it was possible

(*i*) to correlate engine defect reports with hours flown, and hence to get some idea of the relative seriousness of the defects from maintenance and safety considerations;

(*ii*) to review quarterly the failure rate, for ten thousand hours flown, of each engine/aircraft installation, plotted on an engine life basis.

With all engines, the incidence of failure due to engine defects fell during the first fifty hours after installation and then rose fairly uniformly with increased running time. The reasons for the high initial failure rate are not difficult for an engineer to understand, for all reciprocating engines are likely to experience teething troubles in their early life, before the many sliding parts have been properly run in, and before those engines with faults incorporated by human fallibility have been weeded out. Some engine types exhibited a drastic increase in failure rate beyond a fairly well defined life and it was easy to decide what to do with them. Others continued to grow progressively less reliable along a more or less linear curve, and the lives of those between overhauls were determined by fixing a maximum acceptable failure rate, the value of which depended on the danger of engine failure in flight in the aircraft concerned. The economics in pounds, shillings and pence were not worked out—but they very rarely are in time of war and, in any case, the biggest factor of all, the value of human life was imponderable.

Those statistics and failure rate curves were anathema both to squadron engineer officers and to higher authority: they were cursed by the former for increasing still further the number of forms they had to complete and by the latter for questioning the quality of the repaired engines with which they were supplied. However, despite much opposition, they did at last succeed in putting engine reliability statistics on a firm basis, and in getting that basis adopted by the Air Ministry. More tangible results from the points of view of the air crews and of the maintenance personnel were the tightening up of engine overhaul procedure and the wholesale scrapping of early types of "Whistler" engine which had served their purpose and which had become unsafe to operate by current standards.

It was disappointing that Mr. Thornton-Bryar had chosen an American example to illustrate his points, particularly as that example covered only 80 engines. There must be a wealth of statistics available from the wartime reports from Bomber Command, and they could hardly be of any help to an enemy or potential enemy now. The number of aero-engines operated at one time in that Command alone was numbered in tens of thousands, and five hundred "Woofler" heavy bombers having four "Whistler" engines apiece would only have to fly an average of five and a half hours a day to accumulate one million engine flying hours in three months. With figures of that magnitude, statistics were of very real value, and it was more difficult for the person or persons aggrieved by the facts they revealed to take refuge in the popular definitions of statistics and statisticians quoted by the author, although they would always try to do so, particularly if the "Rattler" happened to be doing better than the "Whistler" and the engines were made by rival companies.

In peacetime, it must be almost impossible to obtain a sufficiently large sample of similar marks of engine in similar military aircraft to make statistical data very convincing. In civil aviation it was still more difficult, for a large airline might only operate a hundred aircraft, and it was doubtful if more than twenty-five of those would be alike. For those reasons, he sincerely hoped that the statistical data so painfully acquired in war had been preserved and would one day be published, and he was glad to see that the Engine Reliability Statistics Department which was set up at the Air Ministry at the request of the engineer staff at Bomber Command H.Q. continued in being in peacetime, when such departments were so easily abolished "to economise in staff".

S. B. Bailey, *Assoc. Fellow*

Statistics certainly measured "How we are doing"; Mr. Thornton-Bryar showed that a high number of aero-engines were still too susceptible to defects in their first 50 hours' running, but after this period they seemed to settle down gradually to a more reliable stage of life and then unfortunately, when this useful section of life was reached, the arbitrary time limit made a complete overhaul necessary.

In the interest of economy, longer life was becoming an urgent expedient to make aviation pay; there were many types of British engine which should continue up to 1,000 hours and more with a good safety margin remaining. How, in the opinion of the author, would 1,000 hours between major overhauls affect the economics of aviation?

H. C. Beirs, *Associate*

Mr. Thornton-Bryar was to be congratulated on his careful "cooking" of a statistical example in order to make it digestible to the uninitiated without offending the experienced.

Although I agree with the conclusions made, I would like to suggest another and perhaps, for the rank and file, simpler method of approach.

Mr. Thornton-Bryar rightly points out that the number of observations—from a statistical point of view—is rather small, so that all numerical conclusions may be subject to severe correction in the light of future evidence.

First I propose to eliminate the engines lost through "time expired" from the subsequent statistical analysis, as this deliberately planned "murder" has nothing to do with chance failures but can be rigorously accounted for.

The average technician likes to express failures in percentages: combining Mr. Thornton-Bryar's Tables III and IV gives an opportunity to discuss the correct number to be chosen as the 100 per cent. reference number. Computing the percentage of failures on the numbers which entered each group will show too small a percentage, because the engines left in the group are still exposed to failure. Taking the number "exit" group, will give either too high or too small a value, as it is not known what number of the engines left will fail. The mathematician could give a number of other possibilities, taking the differences between engine entries and engine exits, weighing all these possibilities with probabilities, and so on.

As the evidence is small, it seems reasonable to take simply the mean value of those "entered" and "left," to correct for and possibly even to over-correct, the bias encountered by the reference "engines entered." (The advertising manager of Whistler's most certainly will disagree and favour the method which shows the least percentage.)

The values are given in my Table I A technical man without statistical training will draw a graph of the percentages and happily conclude: We find "Teething troubles" on about two per cent. of the engines put in service. The probability of failure will increase with the life from about two per cent. in the first 50 hours, until it reaches about four to five per cent. at 250 hours. Possibly he will be right, although his own belief will possibly be shaken a bit by the fact that in the last 50 hours no chance failure occurred.

His statistically trained colleague will take a slide rule and trace a diagram of the points $x_1 = B\sqrt{(117.5-5)}$, $y_1 = B\sqrt{5}$; $x_2 = B\sqrt{(111-3)}$, $y_2 = B\sqrt{3}$; and so on.

This diagram, which corresponds to the arc sin transformation due to R. A. Fisher, will give an approximately correct weighing of the evidence in the several groups. The standard error will be nearly independent of p: it is $\frac{1}{2}B$ in the diagram.

He may draw a hypothetical line of four per cent. failure in the average and see that all points observed are inside two parallels to the four per cent. vector in the distance B. This distance corresponds to the inner suspicion limits used in quality control according to B.S. 600R. He will therefore conclude: "until there is further evidence it seems permissible to calculate *as if* the Whistler engines will give failure by chance causes so that four per cent. of the engines in each 50 hours group will, on the average, be lost.

He will show further that the evidence of zero failures in the last group is absolutely compatible with his assumption: on the average 1.24 failures were expected, the log log rule gives the probability to find zero failures in large scale repetition equal to 100 exp $(-1.24)=29$ per cent. and he may use an idle hour to calculate the upper limits of the probability of occurrence with different levels of significance α as $1-(\alpha)^{1/31}$.

Again the advertising manager of Whistler's will disagree and when speaking to higher authorities, will stress the fact that the points are also compatible with the assumption of scarcely three per cent., so that the publication of four per cent. seems a gross exaggeration evidently invented in order to keep Whistler out of business.

The answer of Rattler's advertising consultant, that up to 250 hours of service 16 Whistler's were lost and 73 engines left, which evidently makes up $(16/73)\,100=22$ per cent., shows that the correct judging of percentages would be better if left to people with at least a lustrum of higher mathematical training.

Nevertheless the simple figure of $\bar{p}=4$ per cent. will have a meaning for service estimation and it will be easier to apply than a calculation of rates of loss for 1,000 flying hours.

It simply states: On the average four per cent. of all engines will be lost in each flying month of 50 hours for other causes than "time expired."

Knowing the age of the engines a quick estimation of the replacements required can be obtained and with a slide rule the reserve necessary to meet chance fluctuations around the assumed four per cent. average loss might be calculated.

Considering a risk of error of 1 in 40 as sufficient, the limits are found either by a Poisson table, as in B.S. 600R, or by the Poisson approximation, which can be derived from Fisher's arc sin transformation. If K_α designates the normal standard deviation associated with a unilateral probability to surpass K_α, this approximation is

$$d=(\sqrt{n\bar{p}}\pm\tfrac{1}{2}K_\alpha)^2.$$

Assuming the replacement for time expired to be somewhere between 300 and 350 hours on account of the group classification, Table 2 is obtained which, incidentally, will show the limits of such a simplified calculation. It is by no means probable that the engines lost by the fourth month are the "young" engines. Having globally deducted the average or the maximum expected loss, some engines have been counted twice, *i.e.* in the time expired group and in the chance losses group.

Only technical judgment can decide whether a more elaborate calculation, which takes account of the various age groups separately, is justified.

In this example there is no practical difference and the error is less than that introduced by the sub-grouping of age, which corresponds to a full flying month. In four months the unit will have to rely almost entirely on engines which are to be delivered from now on, that means that the average replacement time of six months is a bit more than halved.

I fully agree with the general conclusions of Mr. Thornton-Bryar's paper that a statistical judgment on the split-up of causes will be impossible until much more experience has been gained.

I would suggest at first a slightly different classification:

A. Serious troubles: troubles which, if they occurred in flight, would involve the immediate emergency landing of a single-engined aircraft, *e.g.* fracture of a crankshaft or connecting rod.

B. Major troubles: troubles which, when occurring in flight, permit further flying for a limited time, but will require the immediate replacement of the engine after landing, *e.g.* slight burning of a valve seat.

C. Minor troubles: troubles which should, or could have been repaired on the aircraft and which do not involve a serious flying risk, but where the engine was replaced for convenience (*e.g.* personnel were available) or as a measure of precaution owing to lack of experience with the engine.

Statistical and technical reasoning leads to a rule-of-thumb method for dealing with these troubles:

A. Every serious trouble must be carefully investigated at once.

B. A major trouble, which occurs for the first time, does not necessarily lead to troublesome investigations: the probability of meeting one particular sort of trouble once among 100 engines is about 10 per cent. if it occurs only once in an average of 1,000 engines.

A second failure of the same kind in about one in three hundred engines tested, makes it imperative to seek for a remedy. The probability that such a failure will occur only once in an average of one thousand engines is only about 0.5 per cent., if it was found twice among 100 engines.

A third failure of the same kind leads to the conclusion that the engine is definitely unsafe in this respect and involves the appropriate technical measures. The probability of meeting the same failure three times among 800 engines tested is only about 5 per cent. if it is found only once in, on the average, 1,000 engines.

C. Minor troubles should be treated by the service departments and should involve larger investigations only if either the repair on the spot is too expensive or if their type and frequency of occurrence endangers the flying readiness of the unit, *e.g.* starter troubles.

TABLE 1

Hours run	*Engines*		*Group number*			*Group*
	lost (i)	*left*	*enter*	*exit*	*mean* ($\bar{n}$)	*percentage* ($\bar{p}=100\,i/\bar{n}$)
0- 50	5	2	121	114	117.5	4.25
50-100	3	3	114	108	111	2.7
100-150	3	15	108	90	99	3.0
150-200	3	34	90	53	71.5	4.2
200-250	2	19	53	32	42.5	4.7
250-300	0	6	32	1		0 +25 lost "time expired"
300-350	0	1				0

TABLE 2

Month	*Engines enter*	*Chance loss average*	*maximum*	*Loss by "time expired"*	*Engines left*	*Necessary replacement*
1st	80	3	7.8	7	63-70	10-17+4%
2nd	70	3	7	19	41-48	22-29+4%
3rd	48	2	6	34	6-12	68-74+4%
4th	12	0	3	15	?	nearly all

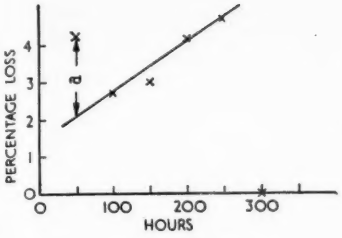


Fig. 1.
Arithmetical plot of the percentages.
a="teething troubles"?

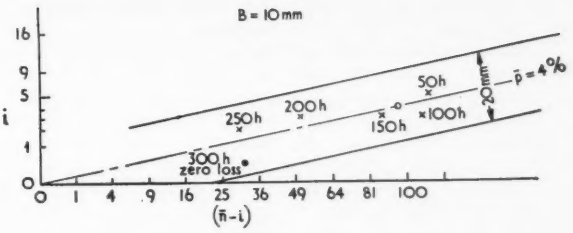


Fig. 2.
Statistical plot of the percentages.
$x, y = 10\sqrt{n}$ mm.
The 20 mm. parallels are the locus of a 1 in 40 chance variation.

The accumulated average chance loss in the first three months is three times 4 per cent. on 80 engines = 9.6 engines lost with an expected limit of $(\sqrt{9.6}+1)^2=17$ engines: a five-inch slide rule will give more precision than is justified by the data.

E. Rossow (France)

MR. THORNTON-BRYAR'S REPLY

Before discussing the points raised by correspondents, he would like to thank others who had privately suggested corrections and fields for further study. There was a misprint in Table V (page 473): it should read:

AGE	LOSSES	HOURS	LOSSES FOR 1,000 HOURS
0- 50	5	5,875	.851
-100	3	5,550	.541
-150	3	4,950	.606
-200	3	3,575	.839
-250	2	2,125	.941
-300	25	825	30.303
-350	0	25	0

TABLE V

Mr. J. D. North had pointed out that on page 470, column 2, there had been an "over-correction" since 8.55 per cent. was a little under seven engines a month and not a little over eight, as inadvertently stated. He also pointed out that if the arithmetic in the next paragraph were formulated as: $\frac{Kn}{Kn+80}\times\frac{100}{n}$, this would tend to zero as n tended to become infinitely great. This was, of course, true and the computation should not be regarded as anything more than an aid to exposure of the fallacy of neglecting part of the population at risk. It was his contention that any formula which neglected age structure was liable to serious error, but perhaps he had insufficiently stressed this view.

Mr. North also raised the question of statistical significance of results. This might be a subject inappropriate for a paper entitled "elementary", but if he might risk excessive simplicity he would refer back to Fig. 1 and the footnote to it, and reiterate that the more information they had, the more likely they were to be right in their conclusions, and the less was the chance that they had picked an exceptionally good (or bad) bunch for examination. Confidence levels, or significance tests, were statistical mathematical tricks for guessing what the odds

were that their conclusions were within some given limits of accuracy. They could go on from stage to stage, testing what the chances were if their guess (on the odds that their conclusion was correct within certain limits) itself fell within certain limits, and they could test whether that chance fell within certain limits. There was no limit to this investigation except in the longevity of the statistician. In this case of aero-engines they could not decide in advance on a sample. They simply collected all the data they could, and at the end of their work calculated once whether the chances were 19 to 1 or 99 to 1 (in betting odds) that they were within a certain percentage of an accurate assessment.

Air Commodore D. F. Lucking had sent him a paper on certain work of his on the mathematical assessment of general unserviceability of aircraft. He thought this to be at once more general, and more mathematically advanced, than the elementary and (he hoped) practical approach which was under discussion. He would like, however, to refer those interested to the 29th January issue of *Nature*, wherein Air Commodore Lucking's paper appeared.

Mr. S. B. Bailey's knowledge of the historical background was more extensive than his. In 1943 he was concerned with climbing about, in, on, and around, military aeroplanes looking for any technical reasons that might prevent their return to base. Only records of engines of interest since 1947 had entered into his calculations, and even those were not really dealt with as fully as he would like. Such matters as the optimum utilisation of technical man power, the ratio of tradesmen required for different tasks, aircraft types, and theatres, how much aircraft flew (and why they did not or could not), and whether the career of a technical officer could be made more attractive to University graduates, all entered into the metrical mysteries of Air Ministry Statisticians. Aero-engine arbitrary lives were brooded upon and decided by a team of highly trained and long experienced R.A.F. officers. It was his job (pleasure and hobby) to help them as much as possible, but only *inter alia.*

Mr. Bailey would no doubt appreciate that the Air Force, together with its civilian advisors, was far from a static organisation. In men the variation from 30,000 to upwards of 1,000,000 and back around the 200,000 mark in a period of about ten years had meant abandonment of much continuous recording (among other dislocations). The frequency of postings, and the devotion of regular airmen's time to the training of N.S.A. personnel (who returned to civil life before very much useful service had been obtained), were all causes of turbulence and improvisation. Engine calculations for obsolete or obsolescent types seemed simply beyond the capacity the Treasury could provide for work of that kind.

He was sorry Mr. Bailey was disappointed that he used American engine rates. It was well known that the R.A.F. had many Harvard and other American aircraft, although in fact the engines used for those rates were of another type now in use (according to the daily papers) in Bomber Command. He presumed Mr. Bailey, like himself, was subject to the retrospective power of security regulations and that he would understand his using only already published, plus fictitious, figures to illustrate his points. After all, it was the method he was seeking to perfect. The examples were purely explanatory.

It was encouraging to find that Mr. Bailey and others had made real efforts to obtain facts on the subject. Naturally the advent of the gas turbine was one of very great importance in this field and the "build-up" of fresh information was likely to be well worth the trouble of collection and analysis. Unfortunately, it was neither a brief nor a cheap process, and unit recording by N.S.A. airmen was not always very reliable. He could wish Mr. Bailey's last sentence were a correct assumption.

It might interest Mr. Bailey that of recent years the current R.A.F. statement that "Reconditioned engines are a farce" was less true than formerly.

Mr. Beirs took the illustrations rather more literally than he would like. He agreed that the more reliable the engine, the longer its life would be, and presumably the more would be the economy. In the Air Force the idea of "making

aviation pay" was not quite the same as for civil operators, and it was fairly safe to say that the frequency of using full throttle was far greater than comparable rates would be for most civil types. Lives and loss rates might well be far better in civil organisations.

As a matter of opinion, he would try to answer his last question, but what he had to say was probably a poorly remembered repetition of what Mr. Peter Masefield once told him.

The economy of longer life in all components of an aircraft was disproportionately greater than the direct financial saving. For example, the extension of the average attainable life from 500 to 1,000 hours might reasonably be expected to approximately halve the cost of overhauls.

But consider these environmental factors. In competition with modernised fleets of other countries it was necessary to replace aircraft with later types before their useful life was exhausted. If five years were a fair length of time before this kind of obsolescence occurred, the entire write-off cost of each aircraft must be recovered in freight charges during the period. That meant a large addition to the minimum economic freight rate that would cover all other costs and depreciation expences.

Obviously the more freight the aircraft carried in five years, the more "thinly" the obsolescence cost could be spread, *i.e.* the cheaper was operation a ton mile. He thought B.E.A.C. aircraft flew about 100 hours a month. If they considered 100 aircraft, that meant in five years about 2.4 million engine hours (assuming four engines an aircraft). That gave about 4,800 engine changes at 500 hours or 2,400 at 1,000 hours. If they assumed, say, one day was taken for teams to change four engines, the extension of life had given one extra aircraft year as well as economising on reconditions costs by 50 per cent., *i.e.* a saving of perhaps £1,200,000 plus £20,000 if it cost £500 to overhaul an engine and an aircraft cost £100,000. An arbitrary extension of life did not make engines more reliable, and if life were arbitrarily extended it might be found that crashes far offset any other saving.

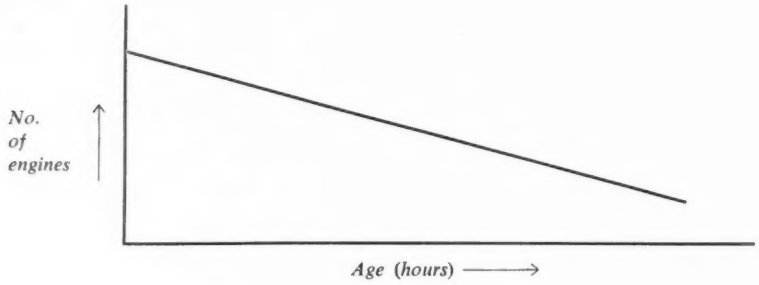
It was his own (cranky?) idea that every aircraft component should carry a money-back guarantee. Operators would buy what component offered the life they could afford. Manufacturers would probably have their risks underwritten and the less reliable components would cost more in premium. Hence the unreliable part guaranteed for 1,000 hours could cost a great deal because the premium might be greater than the original selling price and the manufacturer would have to charge the premium up in his costs, that is, in his selling price. More reliable components guaranteed for 1,000 hours would cost less to insure, and their selling price could be less.

Thus manufacturers would have an economic incentive to compete on reliability. The more reliable the component the cheaper the cost, and presumably the bigger the sale. Unreliable products would be too dear to buy, and well-deserved bankruptcies might follow the production of dangerously shaky equipment. He doubted if this idea could be adopted in practice, but it might merit a little thought.

M. Rossow's congratulations were appreciated, both on the score of method and of conclusions. He proposed to deal serially with some of the points he had raised.

He agreed that "time expired" engines might be eliminated at choice. Table VII gave a breakdown of loss rates attributable to each of six arbitrary classes of reason for loss. The rates were additive horizontally and whatever combination was desired might be selected. For overall planning purposes, and bearing in mind that hours flown were taken as the independent variable, he was inclined to favour this presentation, which was in fact based on the preference of technicians. Percentages were obliged to depend on abitrary assumptions about the hours of use for a calendar period, and this varied due to complicated combinations of casual factors, *e.g.* weather, air crew availability, special exercises, international tension, long and short term policy, availability of spare parts (not necessarily for the engine itself), and so forth.

He agreed that for comparison of one engine type with another, or the same type with itself at different periods, in different theatres, roles, and conditions of usage, some criterion was desirable. An arbitrary population was used to standardise the rates (*see* pages 468-9 July JOURNAL). A simpler linear "ideal" line had been adopted as in the figure below.



Population of engines to which rates are applied.

Life, of course, was arbitrarily curtailed at a point beyond which engines were not permitted to run. Hence, together with the rate for 1,000 hours, it was necessary to state the arbitrary life on which calculations were based.

He must decline to follow M. Rossow through Fisher's transformation because he felt this went beyond the scope of a paper called "elementary," although the use of confidence belts might be worth following up. Too fine a calculation, however, could not be warranted by the nature of the data. For example, it was unrealistic to assume any real homogeneity among the engines over time. Apart from wear and tear the influence of gradual (or sudden) improvement due to modifications and increased knowledge of better handling and servicing techniques were involved.

M. Rossow hit the nail squarely on the head when he suggested classification of engine trouble according to its severity. It was the logical next step. Should the overall rates show something wrong, the rates for individual defects could be derived from the first class of records (mentioned on page 446, paragraph 4, July JOURNAL) combined with the records giving exposure to risk.

This was done when necessary, but mention was not made of it in the original paper because the "dose" of explanation seemed enough for technical readers to stomach at one time.

W. E. Thornton-Bryar

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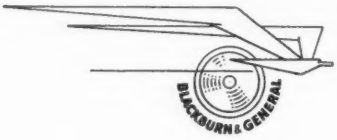

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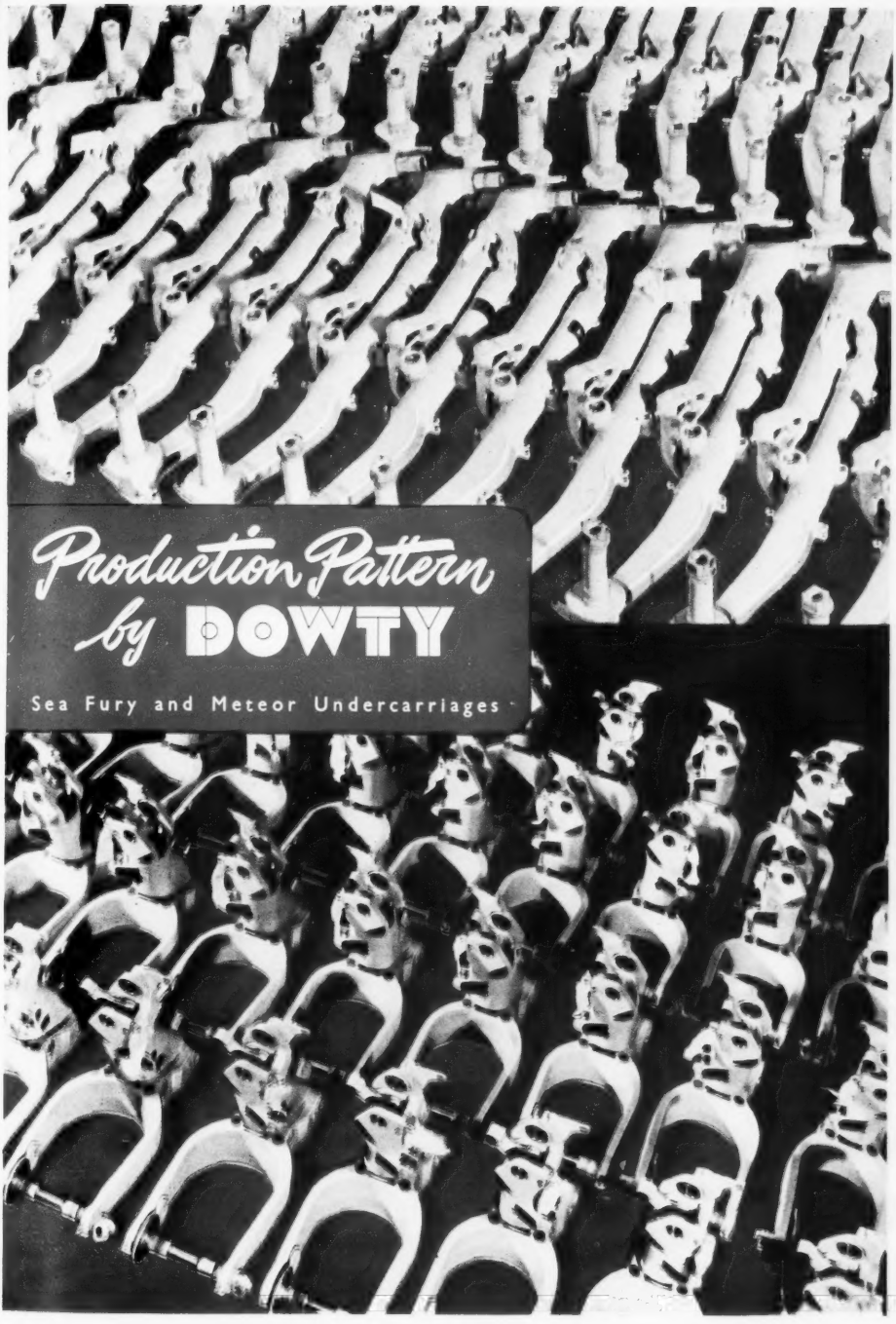

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